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AN AUTOMATIC VEHICLE CLASSIFICATION SYSTEM.(U)

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AN AUTOMATIC VEHICLE CLASSIFICATION SYSTEM

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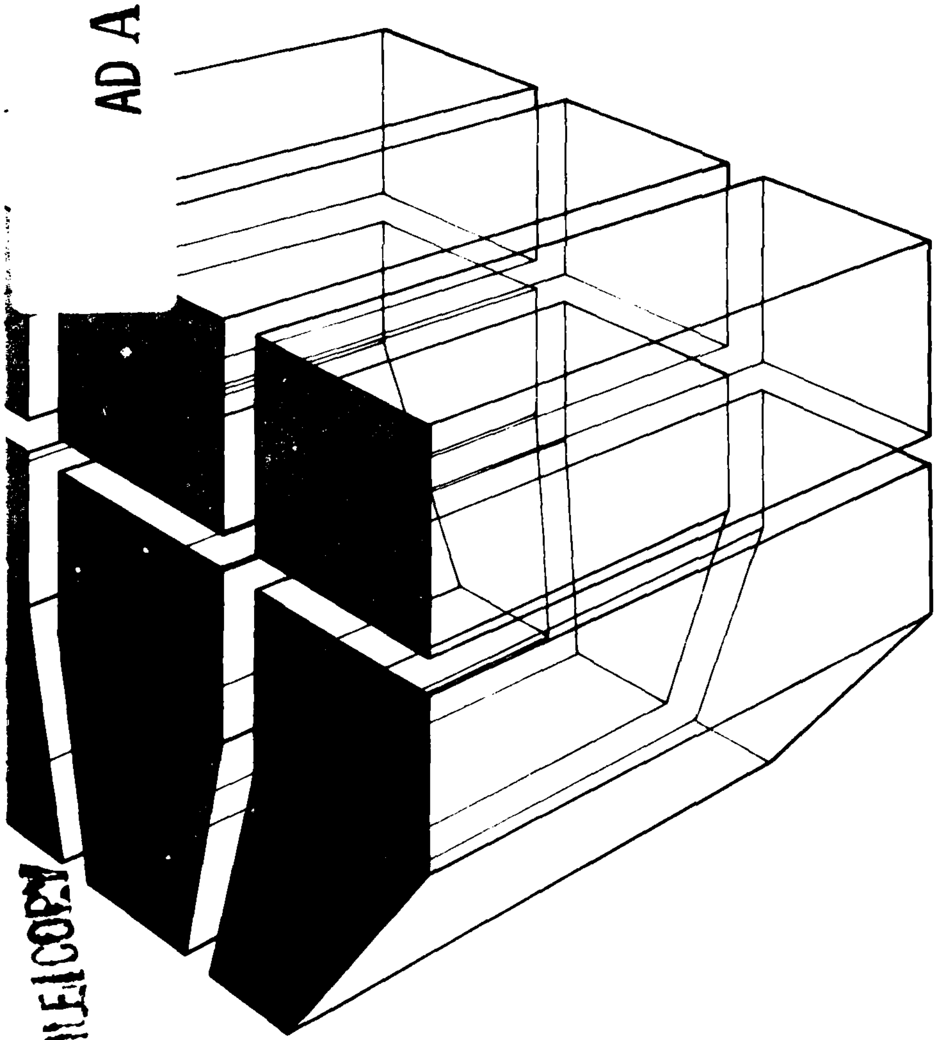

by
Violetta Izabella Pawlowska

CERL

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This manuscript documents the development of an automatic surface transportation identification system to break down vehicle noise sources, by class, into categories of truck, bus, car, and motorcycle. Such a classification would enable the Army, U.S. Environmental Protection Agency and communities to see what contribution each category of vehicles makes to the overall noise at a monitored site. The system designed for this function was based on a configuration of photoelectric emitters and receivers set up along the road at a monitoring site. This system uses hardware-implemented logic and performs a series of algorithms

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on the outputs from the sensors created when a vehicle interrupts the beams as it passes through the system. The unit was tested in a scaled model system; test results indicate that the system is feasible for full scale use. In addition, various portions of the system design can be used by other vehicle study projects, e.g. for projects concerned with vehicle speed or for traffic study projects that require an axle counter or vehicle height indicator.

FOREWORD

This manuscript was submitted in partial fulfillment of requirements for the Master of Science degree in Electrical Engineering at the University of Illinois, Urbana-Champaign.

The work documented in this report was completed at the U.S. Army Construction Engineering Research Laboratory (CERL) for use in acoustical research. The work was performed under the supervision of Dr. Paul Schomer, Leader of the Acoustic Team and Professor of Electrical Engineering at the University of Illinois. Funding for this project was provided to CERL by the U.S. Environmental Protection Agency's Office of Noise Abatement and Control (ONAC) under EPA Reimbursable Order No. 0645. Mr. Casey Cacavain and Mr. Arnold Kenheim were the ONAC project monitors.

Many grateful thanks to my husband, Lincoln Little, for his understanding and helpful suggestions during the course of this project. His support throughout this period was greatly appreciated. Many thanks also to Dr. Paul Schomer for allowing me the chance to create this project.

Dr. R.K. Jain is Chief of CERL-EN. COL L.J. Circeo is Commander and Director of CERL, and Dr. L.R. Shaffer is Technical Director.

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INTRODUCTION

An automatic surface transportation identification system was sought by the U.S. Environmental Protection Agency (EPA), the U.S. Army and others for use with community noise monitoring systems. The purpose of such an identification system is to break down vehicle noise sources by class, into the categories of 1) truck, 2) bus, 3) car, and 4) motorcycle. This classification enables the communities to see what contribution each category of vehicles makes to the overall noise picture at a monitored site. This presently requires an observer at the monitoring site.

The goal of this project was to see if any techniques existed for creating an automatic vehicle identification system or to develop one if a method did not exist which could be feasibly incorporated for use with an outdoor acoustical monitoring system. A prototypical model demonstrating this feasibility and showing the identification system in use was to be constructed.

There were several constraints in terms of the design and operation of the surface noise source identifier system. A major consideration was that the method employed had to be automatic. It could not require immediate or constant human supervision to operate properly. In addition, it could not require human processing to create intelligible results. The data collected could be recorded and stored, to be available for subsequent analysis if automatic, on-site processing was not possible.

Another consideration was that the system had to be non-voluntary. It could not require any cooperation on the part of the vehicle being identified. The vehicle could see the equipment; it did not have to be camouflaged, but the vehicle was not to take an active part in the

identification procedure. Signs could not be put up on the road, for example, asking the traffic to travel at a certain speed.

The system designed had to be able to cover two lanes of traffic travelling in any direction. It also had to provide signals to the acoustical monitoring equipment about when to sample, though the method itself did not have to be based on an acoustical design. The system was to allow samples to be taken only for a single vehicle travelling an appropriate interval away from any surrounding vehicles. The acoustical data was to be valid for just a single source, so the identification system had to determine when a passby of just one vehicle was occuring. It had to be able to decide if there were multiple vehicles in the area monitored.

The proposed system had to be field operable. It had to incorporate as much immunity to weather conditions and lighting as possible. Reasonable portability and ease of set-up would be considered advantages.

APPROACH

The problem of an automatic vehicle identification system was approached by searching out any existing methods of solution and evaluating their feasibility for use with a noise monitoring system. The search yielded very few fruitful ideas. Many possibilities were rejected because they did not meet some of the primary design constraints.

Available Systems

Visual and video methods employing the recording of vehicle images on film were eliminated because they require human processing to yield results. A person has to sit down and look at the pictures taken and then correlate the vehicle type to the event (a pass-by). (5) Optical coded label scanning, similar to that used on railroad cars, was eliminated because it presumes the willingness of the vehicle to be tagged. (6)(13) It also suffers from the problem of the tags getting dirty and being rendered unreadable by the scanning equipment.

The methods which employ a low-power radio transponder mounted under the vehicle to allow interrogation at a roadway site also violate the constraint of not requiring cooperation on the part of the vehicle. (6)(10)(13) Seismic techniques were found to be very dependent on road conditions and physical characteristics of the road surface. (14) Correlations between the data gathered and actual vehicle identifications were not very good if differences in road surface or changes in vehicle speed were incorporated. Techniques which had their basis in acoustical methods such as signature analysis for purposes of unique identification also suffered from poor correlations between the actual data and the resulting classifications. (4)

None of the already available automatic vehicle identification systems appeared to be satisfactory. A design which appeared to have some promise

was an extension of the inductive loop system currently used for traffic counting. (7)(8)(9) A system of identification based on the vehicles' property of mass might be able to incorporate such a detection system. The detection system would be based on the changes which varying masses (vehicles of varying sizes) would have on the inductive properties of the loops as the masses pass over them. The loops would be embedded in the roadway. The range of vehicle speeds was foreseen as a problem with this type of design.

Another promising method employed optical sensing using photocell arrays and logical detection circuitry. (17) In effect, it acted like a one-dimensional image processing system. (Figure 1) The classification of the vehicle was based on the characteristic of length. The vehicle image was focused with a camera lens onto a line of photocells as the vehicle passed by the apparatus. Classification was then determined by the number of photocells covered by the image. The number of photocells covered by a passby was proportional to the length of the vehicle. Vehicles were then grouped into classes of small, medium, and large. This method seemed very elegant since the amount of detection equipment at the roadside was very small. Despite high correlations presented by the author, the system did have weaknesses. One was that it had to be operated in daylight or under artificial illumination. It could not distinguish which lane of traffic the vehicle was in and had no knowledge as to whether there were any other vehicles travelling close to the one that had been identified. (There would be no reason for the system to care if it is used for traffic surveys.) Additional equipment incorporating other technologies would be needed to perform functions such as lane detection, and make them satisfactory for use here. It was also

determined that ambient lighting and variations in vehicle color created problems also. The method is undergoing refinement by the developer (18), but was abandoned for this project in favor of an original approach.

Proposed Method

The method proposed as being feasible for an automatic vehicle classification system still employs optoelectronic components as the basis for detection. Factors of vehicle length, height, and number of axles are used as identification characteristics. In addition, vehicle speed and lane position can be determined by the system. It can send out appropriate signals to acoustical or data-taking units and can satisfy the other constraints required by the EPA.

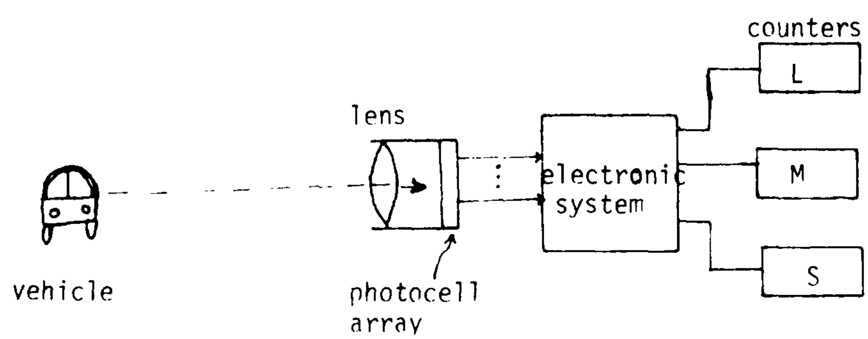


Figure 1. Block diagram of T. Takagi's sensing and discriminating system of moving vehicles.

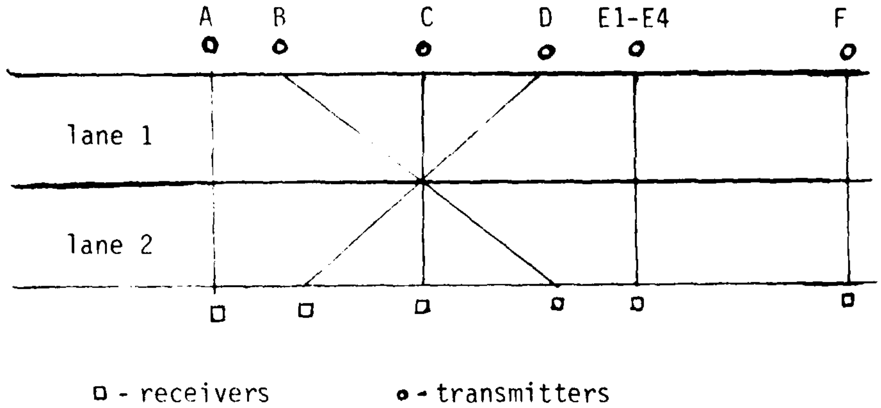
PROPOSED VEHICLE CLASSIFICATION SYSTEM

The proposed system consists of a configuration of pulsed infrared emitters aimed across the roadway at a set of photoelectric detectors. (Figure 2) The detectors are tuned to the frequency at which the emitters are pulsed. This enables the system to be independent of ambient lighting conditions, since the detectors will only respond to the frequency of the beam emanating from their specific mates. (2)

Besides providing the system with immunity to ambient lighting conditions, this type of emitter and detector unit is desirable because it is environmentally safe. The beam produced by the emitter is harmless to both the passing vehicles and to the people in them. The beam is invisible to the naked eye and does not contain undesirable radiation. A person could look directly into an emitter with no ill effects.

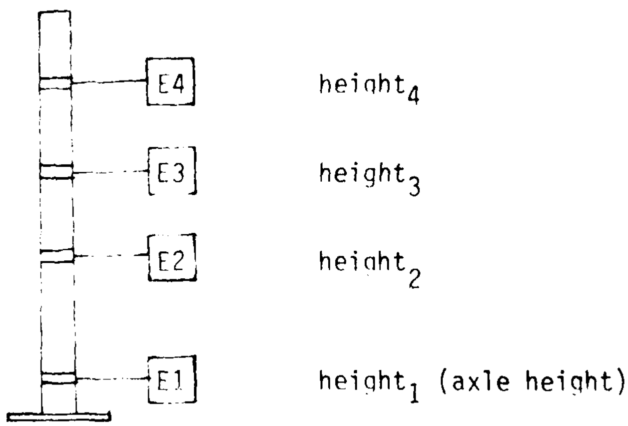
The units produce a logic-compatible output voltage whenever the beam path is interrupted and the receiver no longer detects the presence of a beam. The basis for this identification system is the detection of the voltage change whenever a vehicle blocks a receiver from sensing the beam. The output voltage can be chosen logically high or low to correspond to the detection of the beam by the receivers. This system employs the convention that an interrupted beam will cause the receiver to create a signal which is defined as being logically high.

Algorithms have been developed which determine the lane the vehicle is in, and which provide information about the vehicle's speed, length, height, and axle number based on the order in which the beams are broken and the time interval between the various breaks. A unit has been built for this system which contains the algorithms implemented in hardware logic to preprocess the information coming in from the set of emitter-detector units.



Beams A, B, C, D, and F are created by single pairs of receiver and transmitter units.

Beams E1 through E4 are created with a set of four units arranged one above the other perpendicular to the road.



The beam configuration on the roadway is independent of traffic directions.

Figure 2. Configuration of receiver and transmitter units at a site.

The information that is provided by the preprocessor that has been built for this system does not perform the actual classification of the vehicles into their various categories. The information it yields can be used as the basis for classification after processing by a unit with arithmetic capabilities. The information provided by the preprocessor can either be read after each passby and stored for later processing by the processor unit, or arithmetic and software capabilities could be added to the existing preprocessor unit to achieve on-site processing. Some sort of memory or storage capabilities would also be required to save the results of either the preprocessor unit or any additional unit added on to it.

It should be noted that the detector units can be bought already housed in weatherproof casings and mounts. The preprocessing logic can also be built housed in a weatherproof box with an external, DC power supply, though it is not put in one for the purposes of the prototypical model. The detector units are weatherproof to the extent that the system can be left standing in the rain, but it will only function under the conditions of fog at worst. Heavy rain will disrupt the function of the units by acting as a block to the beam path, though the manufacturer claims that the units will still function in a drizzle. Snow and slush would cover the units, blocking the beams also.

The Vehicle Classification System preprocessor unit consists of several separate functional sections which are overseen by a System Controller that insures that they interplay correctly. Each of the functional sections will be discussed individually. Detailed schematics of each section and all other hardware can be found in Appendix B .

System Scope

The various functional sections of the system preprocessor unit provide information about the vehicle's lane position, the number of axles it has, the transit time across a known distance and the time interval between outer axles. The two times are used to compute the vehicle's speed and length, respectively. The sections also yield information about the vehicle's height and provide signals which can be used to interface the preprocessor to acoustical monitoring equipment, external processors, or data storage devices.

The information provided by the preprocessor unit constructed for this project can be used as the basis for vehicle classification. The classification can be performed by a separate unit which has arithmetic and software capabilities. The preprocessor does not perform the classification. The actual classification must be performed by a different unit which processes the information it has received about the vehicle from the preprocessor.

The first step in the processor's activities would be to perform the actual numerical calculations involved in determining the vehicle's length and speed. Next, it would categorize the vehicle based upon the known characteristics of length, height, and axle number.

Classification would be accomplished by grouping together vehicles with certain sets of characteristics into one category. For example, all two-axled vehicles which are short in height and have a specific length range can be grouped into one category such as cars. Trucks might consist of the group of vehicles which produces characteristics like tall and long, with more than two axles.

It is easy to see that more than just the four categories of car, truck, bus, and motorcycle can be distinguished. A van, for example, would have the characteristics of being a tall, "car"-length, two-axled vehicle. If a distinc-

tion from normal automobiles is desired for vans, such a group of characteristics can have its own class. The software can be written to categorize these characteristics into the class of cars if no such distinction is desired. The classifications which are desired beyond the original four can be determined before the processor is constructed and the software is written for it. The software can be modified if the classifications should change for various applications.

System Errors

This system has been designed to handle two types of errors. The first type of errors are those which are predetermined by the functional specifications of the system. The second type of errors occurs as a result of unexpected environmental factors.

Vehicles travelling next to each other in adjacent lanes, or those travelling too closely to each other do not constitute good samples for the noise monitoring that is to be done. This means that the system must be able to identify such cases and either flag them as errors, informing the processor that a bad acoustical sample has been taken, or else not allow acoustical samples to be taken in the first place. The noise monitoring equipment cannot separate the information provided by two noise sources close together into the portions produced by each source. Thus, the system has been designed to treat such cases as errors.

A beam could be broken by mistake, creating an unexpected result if such a situation was not anticipated in the system design. Such an error might be caused by a bird travelling through the middle set of beams, for example. The system design incorporates the proper logic for handling the case of beams being broken out of sequence.

The system was designed to provide several criteria for classification

in order to decrease the error resulting from categorization based on just one characteristic. The factors of length, height, and number of axles provide a better "picture" of a vehicle than just the factor of length which was used as the basis for classification by Takagi. (17)

SYSTEM FUNCTIONS

Lane Position

The vehicle's Lane Position is determined through the use of beams B, C, and D (Figure 2). This is accomplished by constructing logic to interpret the order in which the beam interruptions occur. The order of the interruptions can be related to the lane in which the vehicle is travelling. The order in which a vehicle breaks this set of beams as it passes through the detector configuration depends on the direction in which it is travelling. Referring to Figure 2, if traffic in both of the lanes is moving from left to right and if a vehicle interrupts:

(1) B, then C, then D, it implies that the vehicle is in lane 1;

(2) D, then C, then B, it implies that the vehicle is in lane 2;

(3) B, then D, then C,
or
(4) D, then B, then C, } it implies that the vehicle is in both lanes.

Cases (3) and (4) would mean that there are either two vehicles travelling next to each other in the two lanes, or that a vehicle is travelling down the middle of the road.

If B and D are reversed in (1) and (2) above, the proper lane position is determined for traffic in both lanes moving from right to left. Interchanging B and D keeps the conditions in (3) and (4) the same.

The case of two-way traffic is somewhat more complicated. It requires this section to know which direction the traffic is coming from before it performs the logic. Thus hardware has been built which informs the system whether a vehicle has entered the beam configuration from the left or from the right. A multiplexor is then used to interchange the function of B and D in the Lane Position algorithm. This enables the vehicle's Lane Position to be determined no matter which direction it enters from.

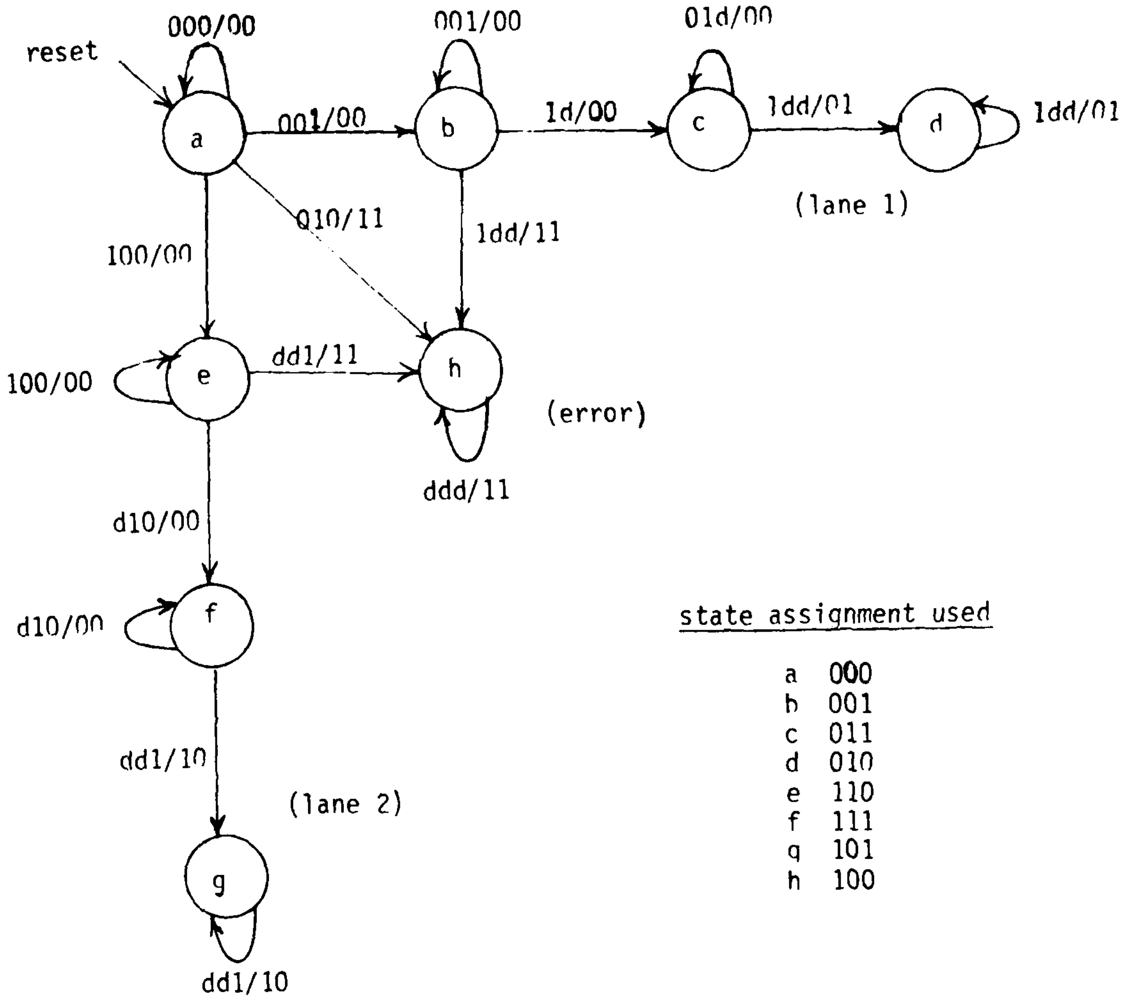
A state machine was designed to perform the logic for this function. The state diagram which was used for the design is presented in Figure 3 . The design of this section was carried out with clocked JK flipflops. A standard state transition table synthesis was performed. This was followed by Karnaugh map minimization to achieve the input functions for the flipflops. The synthesis was performed to satisfy the requirements of the state diagram. (11) Appendix A contains the details of this design.

The state diagram summarizes the inputs required for the machine to go from one state to another and to produce a certain output. The states of the machine are the circled lower-caseletters. The inputs appear on the left of the "/" mark and the outputs appear to the right of it. A state machine can remain in the same state for certain inputs if the design so demands. In this case, the desired output is an indication of which lane the vehicle is in after the state machine recognizes the appropriate sequence of beam breaks which define the vehicle's position. If cases (3) or (4) occur, the machine produces an output which indicates that an error condition has occurred.

This section outputs two bits which specify whether the vehicle is in lane 1, lane 2, or whether an error has occurred. A method of resetting this section after each passby has been included in the design of the System Controller, which oversees all the functions.

Speed and Length

Information about the vehicle's speed and length is gathered with beams C and E1 (Figure 2). The algorithm used for determining speed is motivated by the standard method of timing the vehicle as it travels a known distance. The speed of the vehicle must be known to determine



<u>state assignment used</u>

a	000
b	001
c	011
d	010
e	110
f	111
g	101
h	100

Input requires 3 bits:

B - 001
C - 010
D - 100

Output requires 2 bits:

Z_2Z_1

0 0 - waiting or processing condition (no result yet)
0 1 - vehicle is in lane 1
1 0 - vehicle is in lane 2
1 1 - error condition

Figure 3. State diagram of LANE POSITION function.

its length. The length that is involved here is the distance from the front of the first axle to the back of the last axle. The output that is actually provided by this section is the transit time across a known distance and the time interval between outer axles. The transit time is required to calculate the speed and the speed multiplied by the second time interval yields the length.

The algorithm for this function is summarized in the block diagram of Figure 4. The distance between beams C and E1 has to be greater than the maximum expected vehicle length for the algorith to function properly. This distance has been chosen to be 30 meters for this system. The distance is not fixed and can be adjusted if tests on the road show that it does not need to be so long (or if they show it needs to be longer).

As with the Lane Position function, this algorithm was developed for traffic travelling in only one direction and extended for use with the two-way case through the use of proper multiplexing of beams C and E1. For a vehicle which is travelling from left to right, the algorithm can be summarized as follows:

(1) The clock is started when the vehicle's first axle interrupts C;

(2) The time is noted and stored each time that C is interrupted by the vehicle;

(3) The time when the vehicle's first axle interrupts E1 is noted and stored;

(4) The speed is found by dividing the time noted in (3) by the distance between C and E1 (30 meters);

(5) The length is found by multiplying the speed found in (4) by the last time stored in (2).

The length found in (5) is thought to be a good indicator of the overall length of the vehicle for classification purposes.

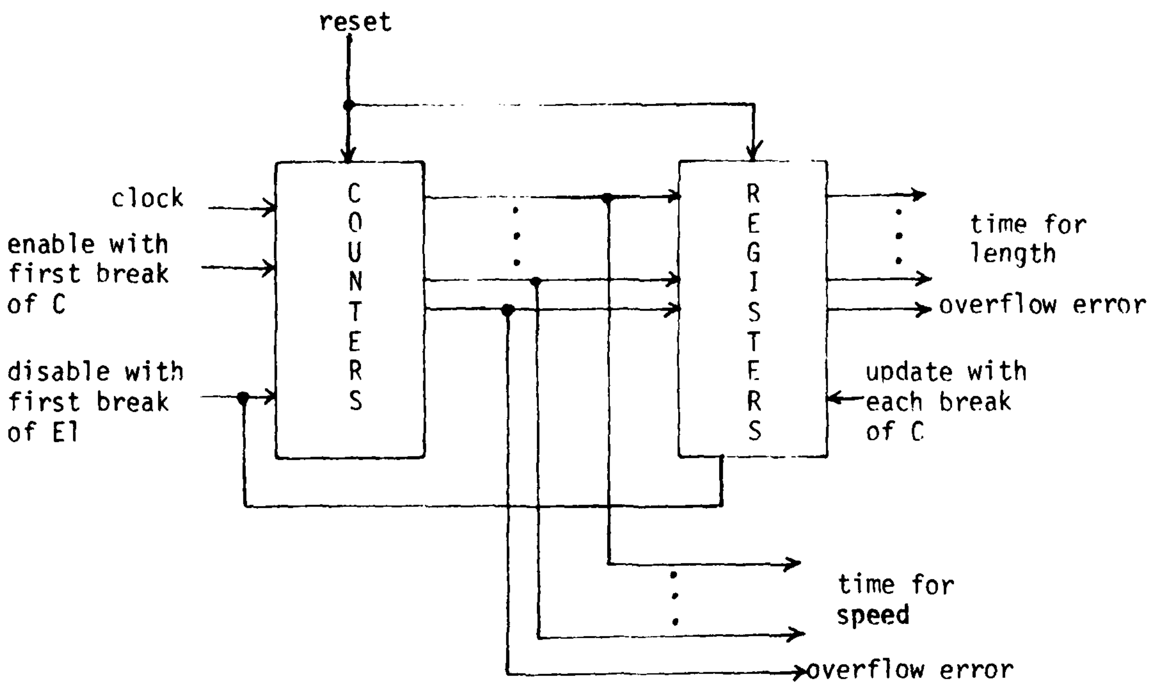


Figure 4. Block diagram of SPEED and LENGTH functions.

The actual calculations in (4) and (5) are not performed by the preprocessor built for this project. It contains no hardware capable of arithmetic operations and has no software capabilities. It provides only the Time for Length and the Time for Speed needed to perform these calculations. The time is put out in system clock units and not in seconds. A processor can perform the actual division and multiplication to provide final results, given the two times and the duration of a system clock unit.

The duration of a system clock unit for this function is influenced by several factors. It involves a tradeoff between the number of bits desired for output, usually as small as possible, and the clock rate which is fast enough to catch the smallest expected duration of a beam interruption. The faster the clock rate, the more bits will be required to store the time it takes a slow-moving vehicle to cross the known distance. The number of counters and registers is determined by the number of bits needed to store the slowest time.

The clock rate is chosen so that as few bits as possible are needed by a slow-moving vehicle, and yet a beam stays broken for at least several clock pulses when interrupted by the axle of a fast-moving one. The range of vehicle speeds for which the system operates varies from 10 km/hr to 120 km/hr. Table 1 presents the timing considerations for this section. After they were all worked out, a clock rate of 500 Hz was chosen. Thus, the times that this function produces in its outputs are in increments of 2 ms for processing purposes.

If a vehicle is travelling below the minimum speed acceptable to this section, the counters will overflow, resulting in an error, and the system will wait for a new passby. An error is also noted by the system if beam E1 is interrupted while beam C is still being interrupted.

Table 1. Timing Considerations.

Speed		Time to travel 30 meters
km/hr	sec/m	(sec)
1	3.6	108.
5	.72	21.6
8	.45	13.5
10	.36	10.8
15	.24	7.2
20	.18	5.4
25	.144	4.32
30	.12	3.6
35	.103	3.09
40	.09	2.7
45	.08	2.4
50	.072	2.16
55	.065	1.95
60	.06	1.8
65	.055	1.65
70	.051	1.53
75	.048	1.44
80	.045	1.35
85	.042	1.26
90	.04	1.2
95	.038	1.14
100	.036	1.08
105	.034	1.02
110	.033	.99
115	.031	.93
120	.03	.90

Using 120 km/hr as the maximum speed, it takes .906 - .900 = .006 sec to differentiate a 1 km/hr difference in speed over the 30 m distance.

It takes only .003 sec to be able to differentiate 10 cm at the maximum speed.

From the above considerations, a clock with a period of .002 sec was chosen to be on the safe side.

In order to set a bound on the number of output bits required, the lowest speed allowed for the system was chosen to be 8 km/hr. This requires 13 output bits with the 500 Hz clock.

The only way that beams C and E1 can be interrupted at the same time as far as the system is concerned, is to have two vehicles travelling too close to each other. This is an error in terms of the design constraints. The preprocessor could be redesigned to allow shorter distances between vehicles. The implementation of the algorithm for speed detection would remain the same, but the one for length would have to be redesigned if a shorter inter-vehicle interval was desired.

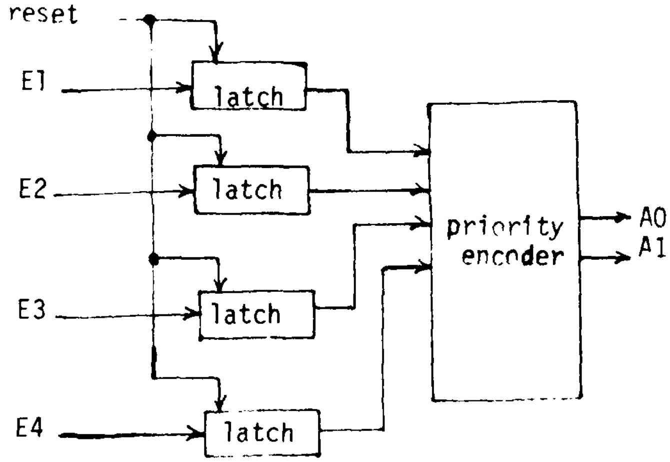
Beams C and E1 reverse their roles to handle traffic travelling in the reverse direction and are multiplexed appropriately according to the vehicle direction as perceived by the system. This section can discriminate differences in length of 10 cm at high-speed ranges, which is fine enough to reflect the difference in length between a motorcycle and a car. The output is produced in 14 bits for Time for Speed and 14 bits for Time for Length, in binary.

Height

Beams E1 through E4 are used to gather information about the Height of the vehicle. (Figure 5) The beams are set up one above the other, perpendicular to the road. (Figure 2) The heights can be chosen such that the detector units are located at axle height, just above car height, at truck cab height, and at truck load height.

A priority encoder is used to show which was the highest beam interrupted by a given vehicle. The taller the vehicle, the higher a beam it will break.

The motivation for this function was to provide a second dimension for characterization purposes. Height can be used to describe vehicle size in the vertical dimension just as length describes it in the horizontal. This provides for a crude type of two-dimensional image processing in terms of the classification algorithm.



Input consists of beams E1 through E4, with E4 being the highest beam.

Output requires 2 bits:

A1	A0	
0	0	- E1 was highest beam broken
0	1	- E2 was highest beam broken
1	0	- E3 was highest beam broken
1	1	- E4 was highest beam broken

Figure 5. Block diagram of HEIGHT function.

This function does not give a side view contour of the vehicle as it passes by. It provides an indication of at least how tall the tallest section of the vehicle is in relation to the tallest section of some other vehicle. The processor that receives this height information from the preprocessor has to know that the height of beam E1 corresponds to x number of meters, the height of beam E2 to y number of meters, and so on.

This section outputs two bits identifying the beam which was broken. It contains no error identification.

Axle Count

The Axle Count section provides a possible third feature for classification. It also provides an additional check to the multiple-lane error indicated by the Lane Position function of the system. This section uses beams C and E1 as inputs.

The purpose of this section is to count the axles of the vehicle at two different points in the beam configuration. It provides the axle number in binary as the four-bit output. An additional bit indicates the occurrence of a mismatch in axle count between the two points where it is determined. A block diagram of this section is presented in Figure 6 .

If the axle count at both points is not the same, it means that somehow, during a single passby, a vehicle has more axles at one time than in another! This would actually occur if vehicles of similar length entered the system simultaneously in the two lanes and then pulled somewhat apart from each other because of a difference in speed (as when one vehicle is passing another). Since the case of two vehicles passing through the system at the same time violates design constraints, an error is noted by this section.

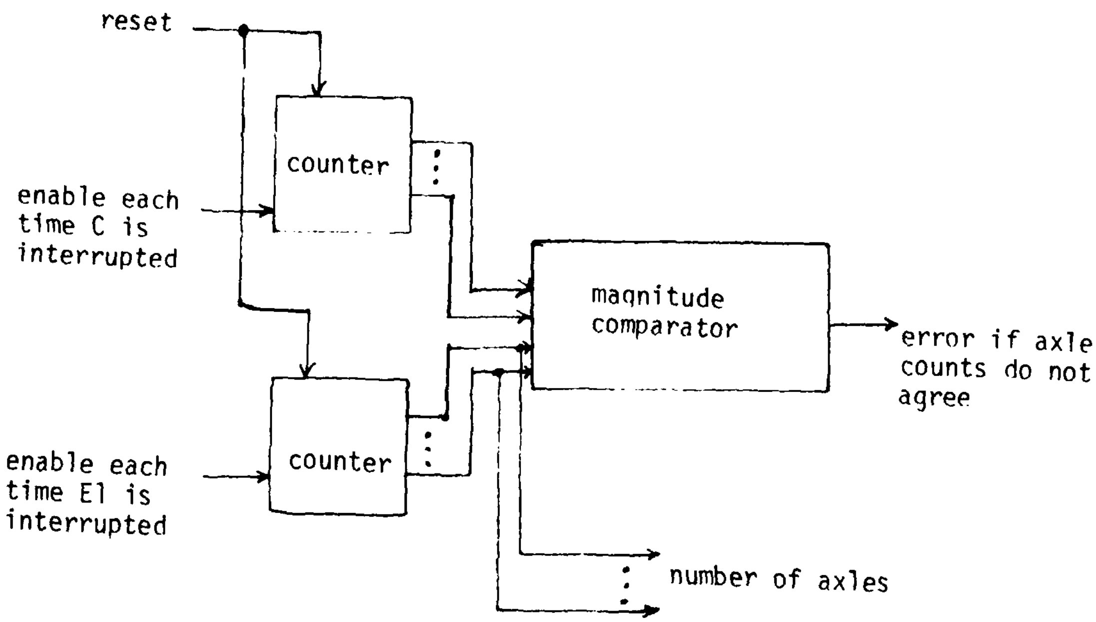


Figure 6. Block diagram of AXLE COUNT function.

Multiplexor

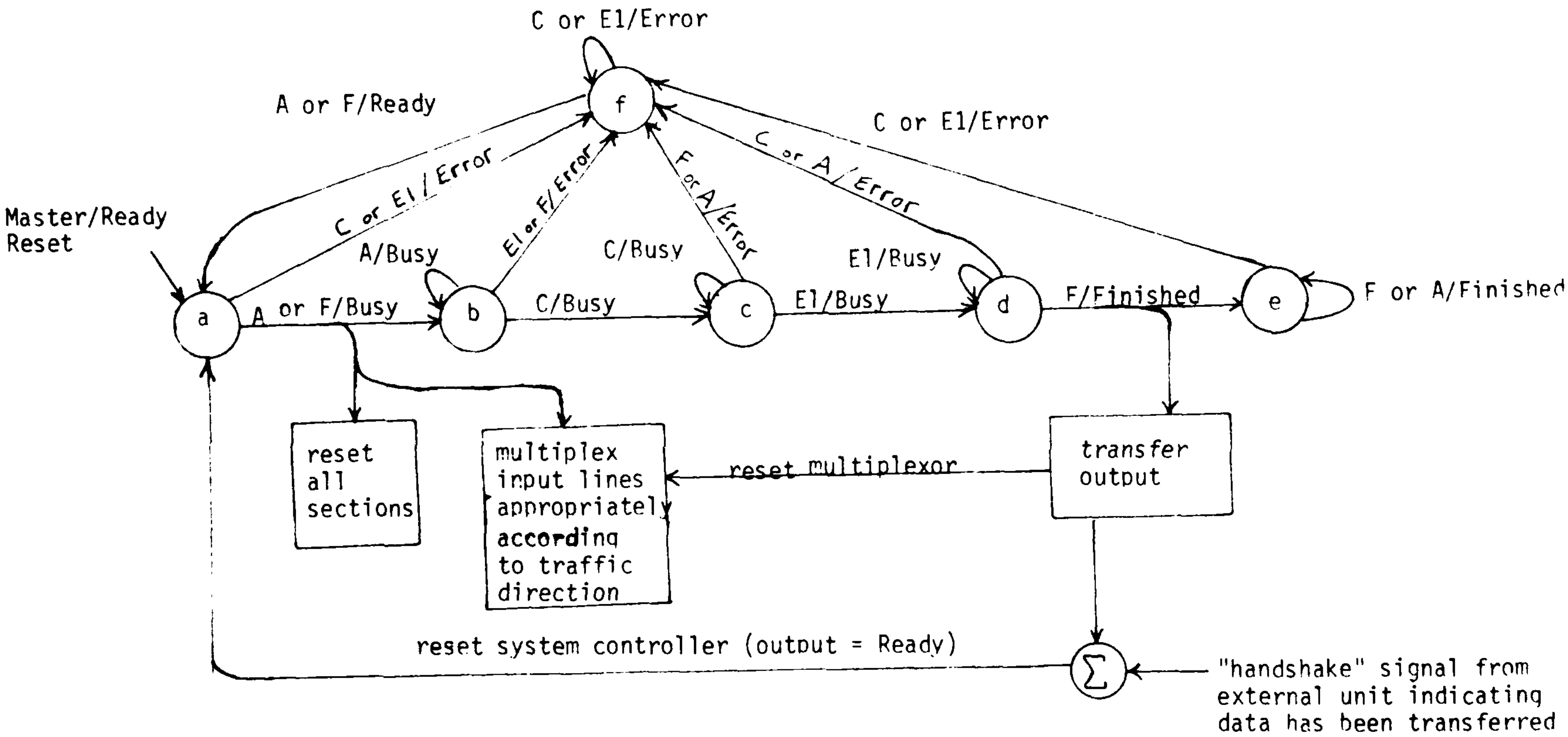
The Multiplexor function keeps track of which direction a vehicle is coming from and then insures that the various system functions receive the signal from the appropriate beams in terms of their algorithms. It also provides some of the system reset signals required by the System Controller to perform its tasks. It is strictly an internal function and provides no output to any external units.

System Controller

One of the functions of the System Controller is to insure that the individual sections of the Vehicle Classification System interact properly. It checks to see that beams are being broken in the proper sequence, given the vehicle's direction with respect to the beam configuration. This sequence detection also provides a means of insuring that only one vehicle is passing through the system at a time, in compliance with the system constraints. The System Controller makes sure that data provided to any external units is flagged as valid or not. It also provides the control signals for turning the acoustical monitoring equipment on and off.

A portion of the System Controller was realized with a state machine design. This involved a procedure similar to that employed for the Lane Position function, but based on the state diagram constructed for this section's logic. The state diagram for the State Controller is presented in Figure 7 . Details of the synthesis performed to satisfy the requirements of the state diagram are contained in Appendix A. The design was realized utilizing JK flipflops. Equations were found for the inputs to the flipflops.

The System Controller oversees the whole system by transferring to a given state, depending on the order in which beams A, C, E1, and F are broken.



Input requires 4 bits:

A - 1000
C - 0100
E1 - 0010
F - 0001

Output requires 4 bits:

Ready - 1000
Busy - 0100
Finished - 0010
Error - 1000

(Z_4 is the low order bit)

state assignment used

a - 000
b - 001
c - 011
d - 010
e - 110
f - 111

Figure 7. Block and state diagram of SYSTEM CONTROLLER.

The Controller outputs provide the system with information as to when sections are to be enabled and when errors occur. The outputs of the state machine are four status bits: "Ready", "Busy", "Finished", and "Error". These are an indication of what state in the state machine the Controller is in at any point in time. The system is "Ready" if it has been reset properly and is waiting to receive the next vehicle. It is "Busy" if beams are being broken in the proper sequence once a vehicle has entered the system and the various sections of the system are functioning normally. "Finished" indicates that a passby is completed. The controller enters an "Error" status if something has gone wrong during the vehicle's passby. Another vehicle entering the system from either direction while a vehicle is already in the configuration will cause an error. The system is eventually reset from an "Error" status once the proper sequence of beams has been broken again. This will occur once the offending vehicles have cleared out of the system. Everything can be reset by a Master Reset signal if it is necessary to clear the system manually, as when it is initially set up.

The System Controller acts as a general error detector. It decides if two vehicles are travelling too closely to each other, or if a vehicle is entering each end of the system at the same time. Both of these are invalid cases. It keeps track of stray beams being interrupted inappropriately. It enables the system to reset itself after such an interruption so tnat it is ready to start over again.

Another very important function that the System Controller performs is to indicate when all the data for a given passby is ready to be transferred to an external device such as a storage unit or processor. It utilizes the "Finished" status bit to allow the preprocessor to "handshake" with those

devices. This insures that the data is actually read before it enables the other systems to reset.

Part of the Controller function which is not implemented with a state machine involves the section which signals the external units. It provides a signal which enables acoustical data to be taken if it determines that a valid passby is occurring. If, during the sampling period, the Controller determines that the system constraints have been violated and that there is an error, it aborts the acoustical sample. In addition, it provides a flag indicating that the sample did not terminate normally. Again, it provides an external unit with a signal indicating when it can read data. It then waits for a "handshaking" signal in return telling it that the data has indeed been read.

Other Functions

The other hardware functions are internal support systems for input and output lines. There are display drivers for a visual display panel. This display allows the outputs to be read without an additional external unit to do the reading. The outputs which are provided are in their raw data form from the preprocessor. A processor unit is still required to perform any numerical computations required and to do the actual classification of the vehicles based on their characteristics.

IMPLEMENTATION

The prototype of the Vehicle Classification System for testing of the design was implemented using TTL, MSI technology. The chips were arranged in wire-wrap sockets onto S-100 boards which fit into a commercial chassis put out by BYTE. The chassis was equipped with a power supply and a motherboard, which allowed for busing of lines between boards. Ribbon cable was used where the bus could not be, such as to the front (display) and back (output line) panels. A total of four boards were needed to fit all of the functions. The chassis is meant to hold ten soldered boards, or will hold five wire-wrapped ones.

The front panel shown in Figure 8 contains LED's indicating the relevant outputs from the various system functions. A set of switches is used to simulate the function of the receiver and transmitter units on the road. These were provided for purposes of debugging the system, as was the hand clock for single-stepping through the two state machines. A Master Reset switch is provided, and so is a Power On indicator light. A switch is also provided to simulate the "handshaking" signal from the external world indicating data has been read. A switch in the "off" (down) position takes the place of an uninterrupted beam, and one in the "on" position plays the role of a beam interruption.

More detailed information about the hardware, including all scnematics, is provided in Appendix B.

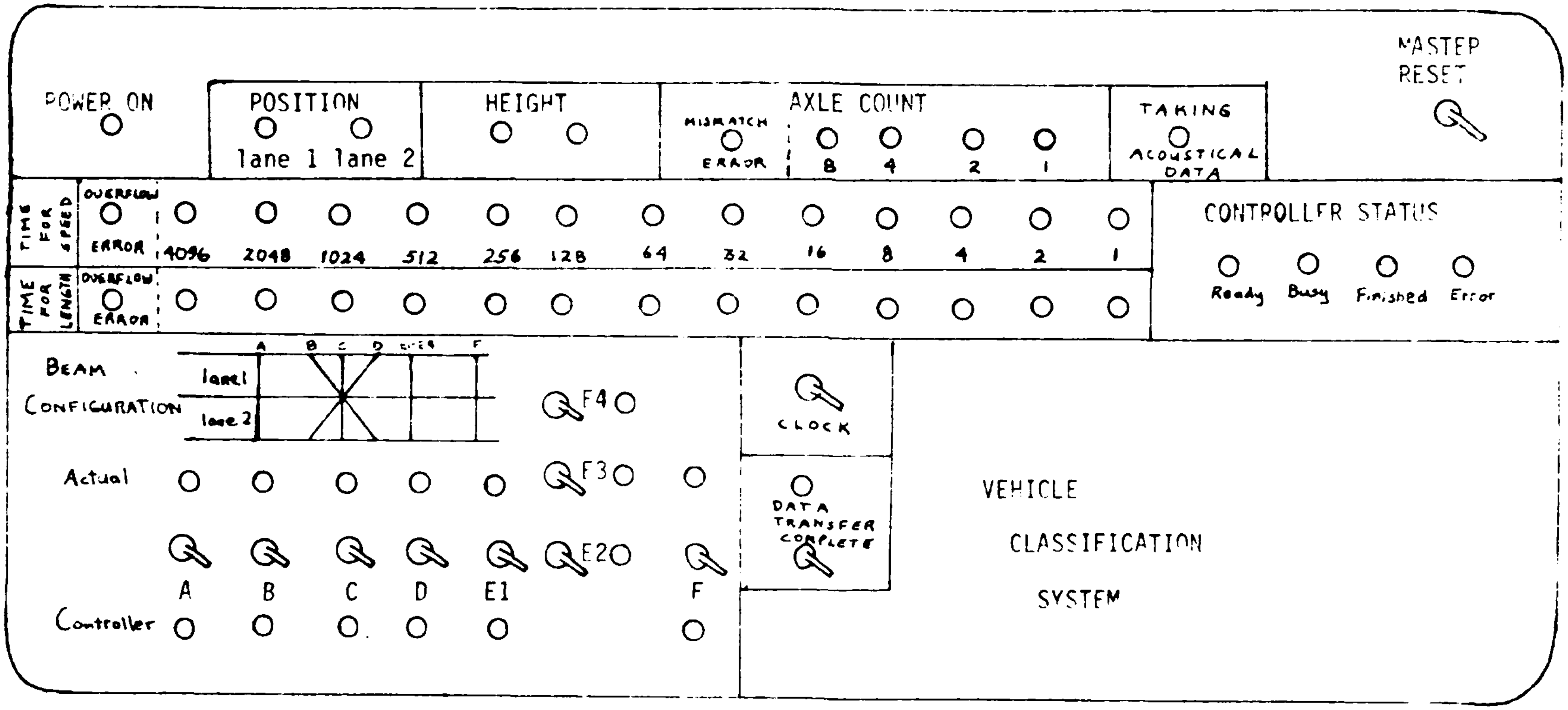


Figure 8. Front panel of the unit.

MODEL

Once it was determined that the system was functioning properly using switches as inputs, it was decided to test the system by creating a scale model road and vehicles. A configuration of smaller beams was also required.

A scale of 1:50 was chosen for the vehicles, but this created problems with the vertical dimension of the system. The emitter and detector units which were available were not on a 1:50 scale to the ones to be used on the road. They were not small enough to create beams which could fit under a scaled car's carriage. This was a necessity in order to be able to distinguish axles. The full scale system would not experience such a problem because the full scale detector units are sufficiently small to create a beam which can pass at the undercarriage level of a car.

The problem was solved by creating vehicle models which are distorted in the vertical dimension. A scale factor of 1:25 was chosen. The dimensions of the various vehicles used to test this system are presented in Table 2 . (16) The silhouettes of the vehicle models used are shown in Figure 9 .

The other main problem with the model involved the choice of what to use for a propelling mechanism for the vehicles to achieve realistic scaled speeds. This was solved by using a scaled train set to give motion to the vehicle models. The models were mounted on top of box cars. The detection units do not "see" the train; the top of the box cars is referenced as the road surface to the system.

The train set was set up on a 4 by 12 foot board. It consisted of three concentric oval tracks. The layout of the model is presented in Figure 10. Lane 1 extends from the edge of one track to the middle of the center track. Lane 2 extends from the middle of that track to the edge of

Table 2. Dimensions of vehicles used for modelling.

	VEHICLE	OVERALL LENGTH	# of AXLES	LENGTH FROM FRONT OF FIRST TIRE TO BACK OF LAST TIRE	OVERALL WIDTH	HEIGHT
1	subcompact 1	3.81	2	2.82	1.50	1.22
2	subcompact 2	4.42	2	3.07	1.65	1.27
3	compact	5.03	2	3.40	1.88	1.28
4	midsize	5.59	2	3.61	2.01	1.27
5	large	5.79	2	3.76	2.03	1.32
6	truck 1	16.76	5	16.41	2.44	4.12
7	truck 2	19.81	5	19.45	2.44	4.12
8	truck cab	4.69	2	4.17	2.44	3.05
9	truck or bus	9.14	2	7.21	2.59	3.05
10	van	4.27	2	3.29	1.83	1.93
11	motorcycle	2.08	2	1.98	.76	1.22

[All measurements in meters.]

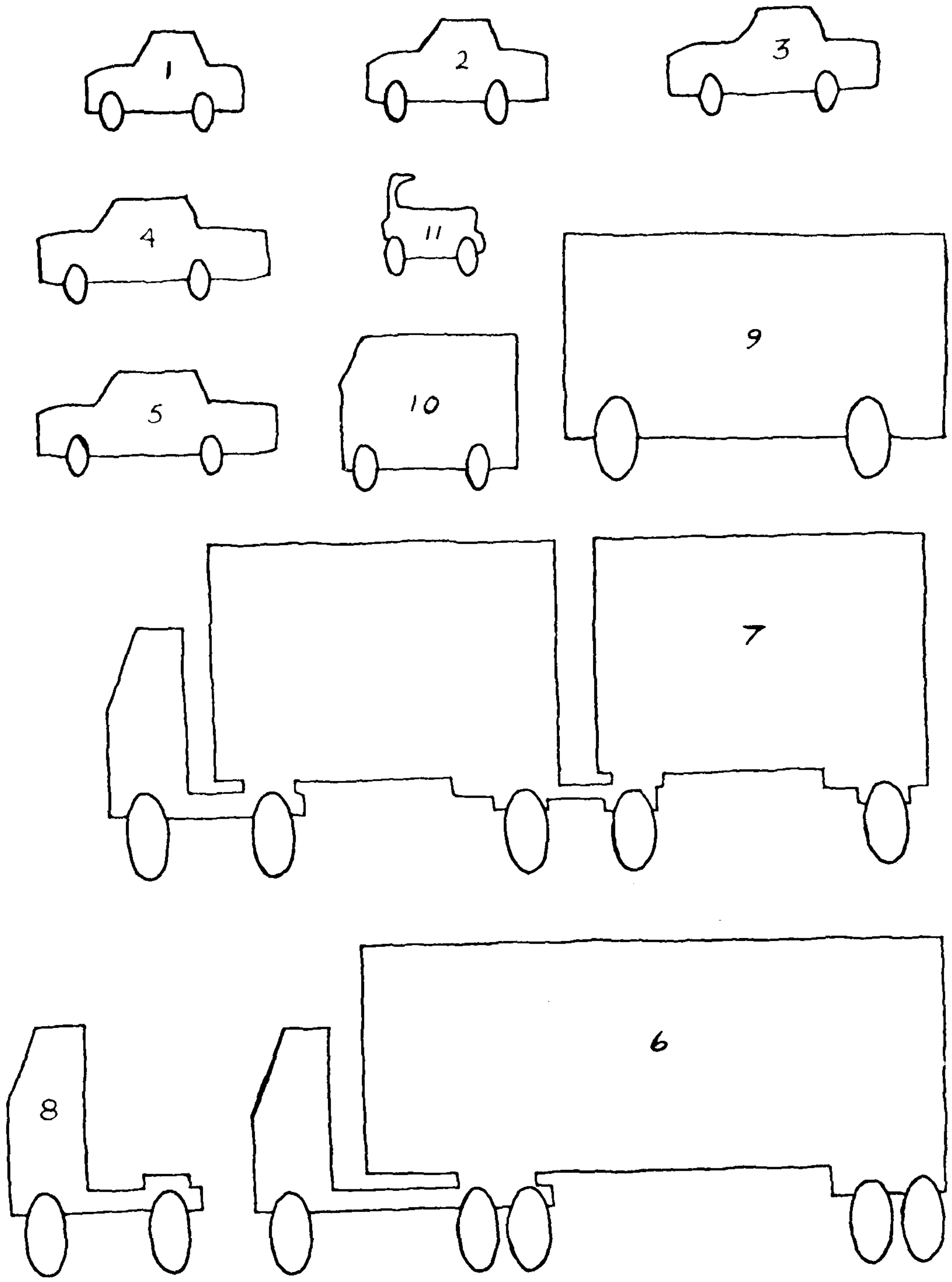


Figure 9. Silhouettes of vehicles used for system modelling.

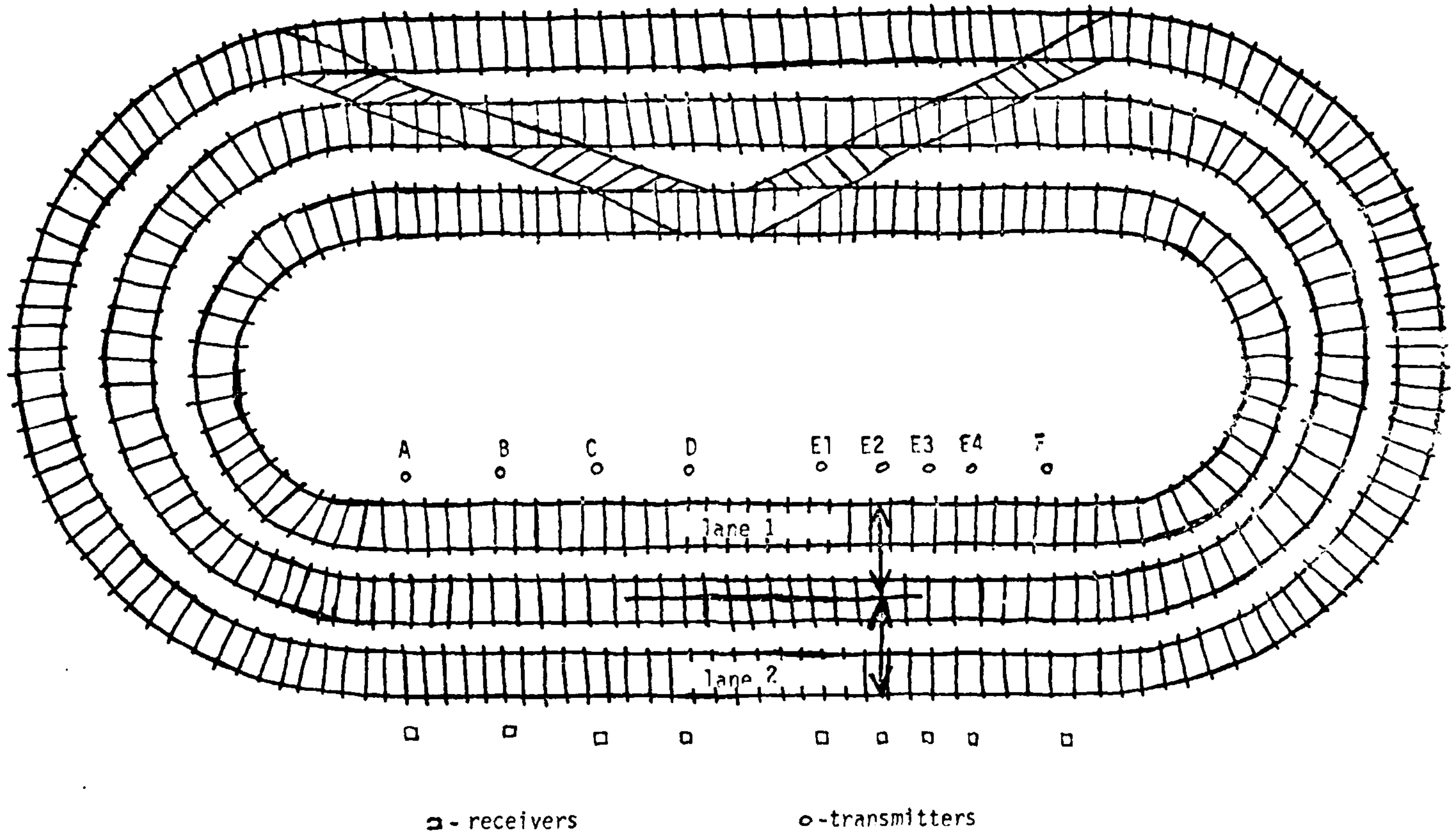


Figure 10. Configuration of the system model (top view).

the third track. The middle track was provided so that the instance of a vehicle travelling down the middle of the road could be simulated. (A train needs a track there to be able to do so.)

Switching tracks were provided at the back side of the tracks so that trains could switch back and forth between any of the three tracks while travelling in either direction. Power can be switched so that the trains on the inner and outer track are able to travel at different speeds and in opposite directions if desired. A vehicle (or train) can never travel down the middle of the road and in a proper lane at the same time. The vehicles' widths would prevent them from doing so.

Receiver and Detector Units

Phototransistors sensitive to the infrared portion of the spectrum were used in the detector units. It turned out that the photodiodes which were matched to these transistors did not emit enough energy to operate over the distances required by the model. (They are normally meant to operate over very small separations, usually less than an inch.) It was discovered that ordinary penlight bulbs emitted enough heat to have the phototransistors respond quite well to them. The penlight bulbs were used as the emitters.

A schematic of the detector circuits is provided in Appendix B . This set of circuits was implemented on a breadboard outside of the unit which houses the preprocessor unit. The outputs were connected to the unit with a ribbon cable. The same port on the back panel of the preprocessor unit can be used to input the outputs from the full scale detectors. The full scale units already have the appropriate circuitry built into their housings and the circuits on the breadboard will not be needed in the full scale system.

Test Results

The testing phase was composed of two sections. One was to check that the characteristics produced by the preprocessor unit were correct for each of the test model vehicles. The other was to exercise the system under known error-causing conditions and see that the system responds properly.

In the first portion, each of the vehicle models was run through the detector configuration in various directions, lanes and at various speeds. The speed of the vehicle was measured independently by being timed with a stopwatch. The data was read from the front panel. The numerical calculations were performed with a hand calculator for the processor unit. The data transferred switch was used to produce the signal which simulated the external "handshaking" signal.

Some actual test statistics are provided in Appendix C. The Lane Position, Axle Count, and Height agreed with the actual characteristics of each of the model vehicles. A 5% discrepancy between the speed calculated from the time provided by the system and the stopwatch based calculation was common. The model is quite hard to time accurately over such short distances by hand. Since the system is effectively providing an electronic timer, it is probably a more accurate indication of the model speed.

The length from Table 2 was compared to the length calculated from the data. The two figures were usually within 5% of each other with the exception of the motorcycle. The discrepancy there was 15%. One reason that the figures may not have agreed exactly was that full scale dimensions were being compared and that meant that a 3-mm difference in the model sizes resulted in a 30-cm difference full scale. Some error was introduced in cutting out the model. Lastly, the train appeared to be having problems

holding a steady speed sometimes. A change in speed while the vehicle is travelling between beams C and E1 would result in an error in the length and speed determined by the system. Vehicles in the full scale system would have to be travelling at pretty much a constant speed over the 30 meter distance for the system to produce accurate results.

Besides checking to see that the statistics provided by the model were proper for the various types of vehicles, known error cases were run through the system to test out the Controller. Cars were sent down the middle of the road; they entered the system at the same time from opposite ends. Vehicles were allowed to pass each other while in the system configuration; they were allowed to follow each other in very short intervals. Vehicles were allowed to stop in the middle of the system while travelling through it. The system was started up with vehicles in it. Beams were interrupted by hand at various points.

Appropriate errors were always indicated and proper action resulted with only one exception. If two vehicles travel less than 30 meters apart from the front of the first car to the rear of the second, the system yields characteristics about this "vehicle" as a proper passby. The description may be of a very long, four-axled vehicle.

The preprocessor cannot correct for this case because it has no arithmetic or software capabilities. The processor unit can catch this instance by having a classification of such "suspiciously" characterized vehicles. Two cars tailgating would have four axles and be very long, but they would still be low in height. The unit can check for combinations of predetermined "odd" characteristics and indicate that they show an error.

CONCLUSION

None of the automatic vehicle identification systems already in existence were suitable for use with the noise-monitoring equipment. An original design was developed to perform this function. It is based on a configuration of photoelectric emitters and receivers set up along the road. The method created uses hardware-implemented logic. It performs a series of algorithms on the output from the units created when a vehicle interrupts the beams as it passes through the system.

The design was implemented in a preprocessor unit which yields data involving characteristics of the vehicles but does not perform the actual classification. This unit was tested in a scaled model system. Results from this model are very positive in indicating the correctness of the design's functions and its feasibility towards full scale use on the road. The preprocessor is able to output the appropriate signals required to interface to external equipment such as noise monitoring units.

Various portions of the design could well be utilized by other projects. The speed detection system can be implemented with only two detector units. It can be utilized for Highway Department projects concerned with vehicle speed. Similarly, other functions of the preprocessor can be used on a stand-alone basis. A height indicator or an axle counter might be useful in a traffic study. Thus sections of this system can be employed with benefit to other systems concerned with various aspects of vehicle study.

APPENDIX A

The figures and table in this section present the details of the transition table systhesis and Karnaugh map minimization performed in the design of the Lane Position function and the System Controller. For additional details of state machine design, see Kohavi (11).

present state	NEXT STATE								OUTPUT Z_2, Z_1							
	D C B								D C B							
$y_1y_2y_3$	000	001	011	010	110	111	101	100	000	001	011	010	110	111	101	100
0 0 0	000	001	100	100	100	100	100	110	00	00	11	11	11	11	11	00
0 0 1	001	001	011	011	100	100	100	100	00	00	00	00	11	11	11	11
0 1 1	011	011	011	011	010	010	010	010	00	00	00	00	01	01	01	01
0 1 0	010	010	010	010	010	010	010	010	01	01	01	01	01	01	01	01
1 1 0	110	100	100	111	111	100	100	110	00	11	11	00	00	11	11	00
1 1 1	111	101	101	111	111	101	101	111	00	10	10	00	00	10	10	00
1 0 1	101	101	101	101	101	101	101	101	10	10	10	10	10	10	10	10
1 0 0	100	100	100	100	100	100	100	100	11	11	11	11	11	11	11	11

Figure 11. State transition and output table for LANE POSITION function.

Circuit change From	To	Required input J	K
0	0	0	d
0	1	1	d
1	0	d	1
1	1	d	0

Figure 12. Excitation requirements for JK flipflops.

J_1

$y_1y_2y_3$ \ DCB	000	001	011	010	110	111	101	100
0 0 0	0	0	1	1	1	1	1	1
0 0 1	0	0	0	0	1	1	1	1
0 1 1	0	0	0	0	0	0	0	0
0 1 0	0	0	0	0	0	0	0	0
1 1 0	d	d	d	d	d	d	d	d
1 1 1	d	d	d	d	d	d	d	d
1 0 1	d	d	d	d	d	d	d	d
1 0 0	d	d	d	d	d	d	d	d

$J_1 = D\bar{y}_2 + C\bar{y}_2\bar{y}_3$

K_1

$y_1y_2y_3$ \ DCB	000	001	011	010	110	111	101	100
0 0 0	d	d	d	d	d	d	d	d
0 0 1	d	d	d	d	d	d	d	d
0 1 1	d	d	d	d	d	d	d	d
0 1 0	d	d	d	d	d	d	d	d
1 1 0	0	0	0	0	0	0	0	0
1 1 1	0	0	0	0	0	0	0	0
1 0 1	0	0	0	0	0	0	0	0
1 0 0	0	0	0	0	0	0	0	0

$K_1 = 0$

Figure 13. Karnaugh maps for J_1 and K_1 functions for LANE POSITION function.

J_2

DCB

$y_1y_2y_3$	000	001	011	010	110	111	101	100
0 0 0	0	0	0	0	0	0	0	1
0 0 1	0	0	1	1	0	0	0	0
0 1 1	d	d	d	d	d	d	d	d
0 1 0	d	d	d	d	d	d	d	d
1 1 0	d	d	d	d	d	d	d	d
1 1 1	d	d	d	d	d	d	d	d
1 0 1	0	0	0	0	0	0	0	0
1 0 0	0	0	0	0	0	0	0	0

$J_2=\overline{D}C\overline{y}_1y_3+D\overline{C}\overline{B}\overline{y}_1\overline{y}_2\overline{y}_3$

K_2

DCB

$y_1y_2y_3$	000	001	011	010	110	111	101	100
0 0 0	d	d	d	d	d	d	d	d
0 0 1	d	d	d	d	d	d	d	d
0 1 1	0	0	0	0	0	0	0	0
0 1 0	0	0	0	0	0	0	0	0
1 1 0	0	1	1	0	0	1	1	0
1 1 1	0	1	1	0	0	1	1	0
1 0 1	d	d	d	d	d	d	d	d
1 0 0	d	d	d	d	d	d	d	d

$K_2=By_1$

Figure 14. Karnaugh maps for J_2 and K_2 functions for LANE POSITION function.

J_3

$y_1y_2y_3$ \ DCB	000	001	011	010	110	111	101	100
0 0 0	0	1	0	0	0	0	0	0
0 0 1	d	d	d	d	d	d	d	d
0 1 1	d	d	d	d	d	d	d	d
0 1 0	0	0	0	0	0	0	0	0
1 1 0	0	0	0	1	1	0	0	0
1 1 1	d	d	d	d	d	d	d	d
1 0 1	d	d	d	d	d	d	d	d
1 0 0	0	0	0	0	0	0	0	0

$J_3=\overline{D}\overline{C}B\overline{y}_1\overline{y}_2+C\overline{B}y_1y_2$

K_3

$y_1y_2y_3$ \ DCB	000	001	011	010	110	111	101	100
0 0 0	d	d	d	d	d	d	d	d
0 0 1	0	0	0	0	1	1	1	1
0 1 1	0	0	0	0	1	1	1	1
0 1 0	d	d	d	d	d	d	d	d
1 1 0	d	d	d	d	d	d	d	d
1 1 1	0	0	0	0	0	0	0	0
1 0 1	0	0	0	0	0	0	0	0
1 0 0	d	d	d	d	d	d	d	d

$K_3=D\overline{y}_1$

Figure 15. Karnaugh maps for J_3 and K_3 functions for LANE POSITION function.

Z_2 lane 2

$y_1y_2y_3$ \ DCB	000	001	011	010	110	111	101	100
0 0 0	0	0	1	1	1	1	1	0
0 0 1	0	0	0	0	1	1	1	1
0 1 1	0	0	0	0	0	0	0	0
0 1 0	0	0	0	0	0	0	0	0
1 1 0	0	1	1	0	0	1	1	0
1 1 1	0	1	1	0	0	1	1	0
1 0 1	1	1	1	1	1	1	1	1
1 0 0	1	1	1	1	1	1	1	1

$Z_2=y_1\bar{y}_2+By_1+C\bar{y}_2\bar{y}_3+DB\bar{y}_2+Dy_1y_2\bar{y}_3$

Z_1 lane 1

$y_1y_2y_3$ \ DCB	000	001	011	010	110	111	101	100
0 0 0	0	0	1	1	1	1	1	0
0 0 1	0	0	0	0	1	1	1	1
0 1 1	0	0	0	0	1	1	1	1
0 1 0	1	1	1	1	1	1	1	1
1 1 0	0	1	1	0	0	1	1	0
1 1 1	0	0	0	0	0	0	0	0
1 0 1	0	0	0	0	0	0	0	0
1 0 0	1	1	1	1	1	1	1	1

$Z_1=y_1\bar{y}_2\bar{y}_3+\bar{y}_1y_2y_3+D\bar{y}_1y_3+By_2\bar{y}_3+DB\bar{y}_1+C\bar{y}_2\bar{y}_3$

Figure 16. Karnaugh maps for output functions of LANE POSITION function.

present state

NEXT STATE

A C EI F

$y_1y_2y_3$	0000	0001	0011	0010	0110	0111	0101	0100	1100	1101	1111	1110	1010	1011	1001	1000
0 0 0	000	001	111	111	111	111	111	111	111	111	111	111	111	111	111	001
0 0 1	001	111	111	111	111	111	111	011	111	111	111	111	111	111	111	001
0 1 1	011	111	111	010	111	111	111	011	111	111	111	111	111	111	111	111
0 1 0	010	110	111	010	111	111	111	111	111	111	111	111	111	111	111	111
1 1 0	110	110	111	111	111	111	111	111	111	111	111	111	111	111	110	110
1 1 1	111	000	111	111	111	111	111	111	111	111	111	111	111	111	111	000

OUTPUTS Z_1, Z_2, Z_3, Z_4

A C EI F

$y_1y_2y_3$	0000	0001	0011	0010	0110	0111	0101	0100	1100	1101	1111	1110	1010	1011	1001	1000
0 0 0	1000	0100	0001	0001	0001	0001	0001	0001	0001	0001	0001	0001	0001	0001	0001	0100
0 0 1	0100	0001	0001	0001	0001	0001	0001	0100	0001	0001	0001	0001	0001	0001	0001	0100
0 1 1	0100	0001	0001	0100	0001	0001	0001	0100	0001	0001	0001	0001	0001	0001	0001	0001
0 1 0	0100	0010	0001	0100	0001	0001	0001	0001	0001	0001	0001	0001	0001	0001	0001	0001
1 1 0	0010	0010	0001	0001	0001	0001	0001	0001	0001	0001	0001	0001	0001	0001	0010	0010
1 1 1	0001	1000	0001	0001	0001	0001	0001	0001	0001	0001	0001	0001	0001	0001	0001	1000

Figure 17. State transition and output tables for SYSTEM CONTROLLER.

J_1

$y_1y_2y_3$ \ A C E1 F	0000	0001	0011	0010	0110	0111	0101	0100	1100	1101	1111	1110	1010	1011	1001	1000
0 0 0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0 0 1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0
0 1 1	0	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1
0 1 0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
1 1 0	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
1 1 1	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d

$J_1=(A+E1+F+y_1+\overline{y}_3)(C+E1+F+y_1+y_2)(A+C+F+\overline{y}_2)(A+C+E1+y_1+y_2+y_3)$

K_1

$y_1y_2y_3$ \ A C E1 F	0000	0001	0011	0010	0110	0111	0101	0100	1100	1101	1111	1110	1010	1011	1001	1000
0 0 0	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
0 0 1	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
0 1 1	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
0 1 0	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
1 1 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1 1 1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1

$K_1=\overline{ACE1}Fy_2y_3+A\overline{CE1}\overline{F}y_2y_3 = \overline{CE1}y_2y_3(\overline{A}F+A\overline{F})$

Figure 18. Karnaugh maps for J_1 and K_1 functions for SYSTEM CONTROLLER.

J_2

A C E1 F

$y_1y_2y_3$	0000	0001	0011	0010	0110	0111	0101	0100	1100	1101	1111	1110	1010	1011	1001	1000
0 0 0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0 0 1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0 1 1	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
0 1 0	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
1 1 0	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
1 1 1	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d

$J_2=(C+E1+F+y_1)(A+C+E1+y_1+y_3)$

K_2

A C E1 F

$y_1y_2y_3$	0000	0001	0011	0010	0110	0111	0101	0100	1100	1101	1111	1110	1010	1011	1001	1000
0 0 0	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
0 0 1	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
0 1 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0 1 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1 1 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1 1 1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1

$K_2=\overline{ACE1}Fy_1y_2y_3+A\overline{CE1}\overline{F}y_1y_2y_3 = \overline{CE1}y_1y_2y_3(\overline{A}F+A\overline{F})$

Figure 19. Karnaugh maps for J_2 and K_2 functions for SYSTEM CONTROLLER.

J_3

A C E1 F

$y_1y_2y_3$	0000	0001	0011	0010	0110	0111	0101	0100	1100	1101	1111	1110	1010	1011	1001	1000
0 0 0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0 0 1	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
0 1 1	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
0 1 0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
1 1 0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0
1 1 1	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d

$J_3=(A+C+E1+\overline{y}_2)(C+E1+\overline{y}_1+\overline{y}_2)(A+C+E1+F+y_1)(A+C+F+y_1+\overline{y}_2)$

K_3

A C E1 F

$y_1y_2y_3$	0000	0001	0011	0010	0110	0111	0101	0100	1100	1101	1111	1110	1010	1011	1001	1000
0 0 0	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
0 0 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0 1 1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
0 1 0	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
1 1 0	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
1 1 1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1

$K_3=\overline{AC}E1\overline{Fy}_1y_2+\overline{ACE1}Fy_1y_2+A\overline{CE1}\overline{F}y_1y_2 = \overline{AC}E1\overline{Fy}_1y_2+\overline{CE1}y_1y_2(\overline{A}F+A\overline{F})$

Figure 20. Karnaugh maps for J_3 and K_3 functions for SYSTEM CONTROLLER.

Z_1 Ready

$y_1y_2y_3$ \ A C E1 F	0000	0001	0011	0010	0110	0111	0101	0100	1100	1101	1111	1110	1010	1011	1001	1000
000	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
011	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
010	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
111	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1

$Z_1=\overline{ACE1F}\,\bar{y}_1\bar{y}_2\bar{y}_3+\overline{ACE1}Fy_1y_2y_3+A\overline{CE1F}y_1y_2y_3 = \overline{ACE1F}\,\bar{y}_1\bar{y}_2\bar{y}_3+\overline{CE1}y_1y_2y_3(\bar{A}F+A\bar{F})$

Z_2 Busy

$y_1y_2y_3$ \ A C E1 F	0000	0001	0011	0010	0110	0111	0101	0100	1100	1101	1111	1110	1010	1011	1001	1000
000	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
001	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
011	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
010	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
111	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

$Z_2=\overline{ACF}\,\bar{y}_1y_2+\overline{AE1F}\,\bar{y}_1y_3+A\overline{CE1F}\,\bar{y}_1\bar{y}_2+\overline{ACE1}F\bar{y}_1\bar{y}_2\bar{y}_3$

Figure 21. Karnaugh maps for output functions for SYSTEM CONTROLLER.

Z_3 Finished

A C E1 F

$y_1y_2y_3$	0000	0001	0011	0010	0110	0111	0101	0100	1100	1101	1111	1110	1010	1011	1001	1000
0 0 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0 0 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0 1 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0 1 0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1 1 0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1
1 1 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

$Z_3=\overline{CE1}y_1y_2\bar{y}_2+\overline{ACE1}Fy_2\bar{y}_3$

Z_4 Error

A C E1 F

$y_1y_2y_3$	0000	0001	0011	0010	0110	0111	0101	0100	1100	1101	1111	1110	1010	1011	1001	1000
0 0 0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0 0 1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0
0 1 1	0	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1
0 1 0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
1 1 0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0
1 1 1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0

$Z_4=(C+E1+F+y_1+y_2)(A+C+F+y_1+\bar{y}_2)(C+E1+\bar{y}_1+\bar{y}_2+y_3)(A+E1+F+y_1+\bar{y}_3)(A+C+E1+y_1+y_3)(A+C+E1+\bar{F}+\bar{y}_1+\bar{y}_2)(\bar{A}+C+E1+F+\bar{y}_1+\bar{y}_2)$

Figure 22. Karnaugh maps for output functions for SYSTEM CONTROLLER.

Table 3. Equation simplification for SYSTEM CONTROLLER equations.

The following set of variables is defined in order to simplify the system controller equations. This reduces the number of inputs per gate, allowing implementation with commonly available chips.

$X=\bar{A}F+A\bar{F}$

$\alpha=\gamma y_1 y_3 X$

$\beta=\lambda \bar{y}_3 \delta$

$\gamma=\bar{C}y_2$

$\delta=\bar{A}\bar{E1}$

$\lambda=\bar{y}_1\bar{y}_2\bar{C}$

$\omega=y_1\gamma$

$\zeta=A+y_1$

$\eta=C+E1$

$\mu=\bar{y}_1+\bar{y}_2$

$\psi=\eta+F+y_1+y_2$

$\theta=\zeta+E1+F+\bar{y}_3$

$\phi=\zeta+C+F+\bar{y}_2$

The system controller equations take the following form after the variables are substituted appropriately:

$J_1=\theta\psi(A+C+F+\bar{y}_2)(\zeta+\eta+y_2+y_3)$

$J_2=(\eta+F+y_1)(\zeta+\eta+y_3)$

$J_3=(A+\eta+\bar{y}_2)(\eta+\mu)(\zeta+\eta+F)$

$K_1=\gamma\bar{E1}y_3X$

$K_2=\bar{E1}\alpha$

$K_3=AE1\bar{F}\omega+\gamma\bar{E1}y_1X$

$Z_1=\beta F+\bar{E1}\alpha$

$Z_2=\bar{A}F+\delta Fy_1y_3+AE1\bar{F}\lambda+F\beta$

$Z_3=\bar{E1}y_1\bar{y}_3\gamma+\delta F\bar{y}_3\gamma$

$Z_4=\phi\zeta(\eta+\mu+y_3)\theta(\eta+\zeta+y_3)(A+\eta+F+\omega)(\bar{A}+\eta+F+\mu)$

APPENDIX B

The figures and tables of this section present the schematics and details of the hardware used in the design of the Vehicle Classification System preprocessor. Additional details about the S-100, BYTE-8 chassis are available in the manufacturer's specifications. The chassis comes with a power supply which can provide +8, +18, and -18 volts. Each board in the chassis has an on-board power regulator and input-output capacitors to provide +5 volts as the logically high signal. The front panel of the standard chassis has been modified in order to display the outputs from the various system functions.

Input and output connectors have been provided on the back panel. The inputs consist of the outputs from the detectors -- either the full size units or the model ones. These are fed into the top connector on the back panel. The unit's outputs can be accessed from the next two connectors on the back panel. The outputs are sent out in negative logic. The have to be inverted at the receiving unit in order to be read properly. Grounding caps have been created for the inputs on the connectors. (The output connector has one input connection in the form of receiving the "handshaking" signal from the external unit.) These are used to tie the inputs low when the system is being operated from the front panel switches, and no external inputs are connected to it. The output line definitions are specified in Figure 9. Ribbon cable connectors are provided to make these outputs readily accessible for interfacing to an external unit.

Table 4 . Hardware labelling conventions and contents.

References to chips are made by board, row, and column.

The boards are labelled α, β, γ, and δ. There is also one external breadboard.

The rows are labelled A, B, C, and D.

The columns are labelled Z, Y, X, W, V, T, S, R, P, N, M, L, and K.

Ribbon cable connectors are labelled with lower-case letters, with subscripts indicating which end is referred to.

Connector	Size	Location
a_1	20 pin	board α
a_2	20 pin	board β
b_1	20 pin	front panel
b_2	20 pin	board α
c_1	50 pin	board α
c_2	50 pin	front panel
d_1	20 pin	board α
d_2	20 pin	front panel
e_1	20 pin	board β
e_2	25 pin	back panel
f_1	50 pin	board δ
f_2	25 pin	back panel
f_3	25 pin	back panel

Board α contains	Display drivers Switch debounce
Board β contains	System controller Multiplexor Input buffers
Board γ contains	Lane detection Clocks Axle counter Signals to acoustical or data-taking units
Board δ contains	Length and Speed Height Output drivers

Breadboard contains receiver detection circuitry.

Any signals put out onto the S-100 bus are denoted by a number enclosed in a circle on the schematics.

Table 5a. S-100 bus signal definitions.

PIN #	SIGNAL IDENTIFIER		POINT OF ORIGIN
1	+8 volts		
2	+18 volts		
3			
4	A		βBN6
5	B		βCN6
6	C		βDN6
7	D		βCN12
8	E1		βDN12
9	F		βBN12
10	$\overline{A}$		βBN8
11	$\overline{B}$		βCN8
12	$\overline{C}$		βDN8
13	$\overline{D}$		βDN2
14	$\overline{E1}$		βBY6
15	$\overline{F}$		βCN2
16	C_d		βAN4
17	$\overline{C}_d$		βAN6
18	$\overline{E1}_d$		βAN8
19	$\overline{E2}_d$		βAN10
20	$\overline{E3}_d$		βAN12
21	$\overline{E4}_d$		βBN2
22	$\overline{\text{Master Reset}}$		α - column m
23	$\overline{\text{Done}}$		βBY10
24	$\overline{\text{Start Clear}}$		βBY8
25	Data Transfer Complete (System)		αCK3
26	Data Transfer Complete (External)		δBJ6
27	Ready	Controller Status	βBW3
28	Busy		βDV8
29	Finished		βBW8
30	Error		βBX3
31			

Note: Pins enclosed in parentheses have been dedicated by the chassis manufacturer and cannot be used by this system.

Table 5b. S-100 bus signal definitions.

PIN #	SIGNAL IDENTIFIER		POINT OF ORIGIN
32	Z_1	Axle Count	γBR15
33	Z_2		γBR14
34	Z_3		γBR13
35	Z_4		γBR12
36	Error		γAT8
37	Z_1	Height	δDS9
38	Z_2		δDS7
39	Z_1	lane 1	γBV8
40	Z_2	lane 2	γAV8
41			
42	System Clock (4000 Hz)		γBK3
43			
44			
(45)	SOUT		
46			
47			
48	500 Hz Clock		γAK12
49			
50	Ground		
51	+8 volts		
52	-18 volts		
53	Acoustical Data Aborted		γAP9
54	Taking Acoustical Data		γDR5
(55)	RTC		
56	Z1	Time for Speed	δDX5
57	Z2		δDX9
58	Z3		δDX2
59	Z4		δDX12
60	Z5		δCX5
61	Z6		δCX9
62	Z7		δCX2
63	Z8		δCX12
64	Z9		δBX5
65	Z10		δBX9
66	Z11		δBX2

Table 5c. S-100 bus signal definitions.

PIN #	SIGNAL IDENTIFIER	POINT OF ORIGIN
67	Z12	δBX12
(68)	MWRITE	
69	Z13	δAX5
70	Z14 - Overflow Error	δAX9
71		
72	$\boxed{E2}$	βAK6
73	$\boxed{E3}$	βAK8
74	$\boxed{E4}$	βAK11
75	Data Available to be Read	γBP3
76		
(77)	PWR	
78	Z15	δDW15
79	Z16	δDW14
80	Z17	δDW13
81	Z18	δDW12
82	Z19	δCW15
83	Z20 Time for	δCW14
84	Z21 Length	δCW13
85	Z22	δCW12
86	Z23	δBW15
87	Z24	δBW14
88	Z25	δBW13
89	Z26	δBW12
90	Z27	δAW15
91	Z28 - Overflow Error	δAW14
92	$\boxed{A}$	βAL3
93	$\boxed{B}$	βAL6
94	$\boxed{C}$	βAL8
95	$\boxed{D}$	βAL11
96	$\boxed{E1}$	βAK3
97	$\boxed{F}$	βAJ3
98	Hand Clock (single step)	γAW5
99		
100	Ground	

Table 6. Semiconductor components listed by boards.

	Board α	Board β	Board γ	Board δ
7400		AW, BW	BK, BY, CY	
7402		AT	CP	
7404		AN, BN, CN, DN, AY, BY	AS, AY	AJ, BJ, AK, BK, CK, AL, BL, CL, AS, AY
7406	AN, BN, CN, DN, AR, BR, CR, AT, BT, CT			
7408		AM, AX, BX	BP, AT, DY	AV, BY
7410		CW	BX, CX, DX	
7411		CX		
7420		CV, DV, DW	CW, DW	
7421		DX		
7423		DR, AS BS, CS, DS	AR	
7427		BT, CT, DT		
7430			AV, BV, CV, DV	
7432	CK	AJ, AK, AL, DY	DS	
7474	AW, BW, CW, AX, BX, CX	AP	AP,DR	BS, CS, CY, DY
7476		AV, BV	AW, AX	
7485			CR	
7486		CY		
74148				DS
74157		BP, CP		
74177			AK, BS, CS	AX, BX, CX, DX
74195				AW, BW, CW, DW
CD4050BE		CL, CM		
CD4093B	Used on breadboard only			
SE555			DK	
MRD450	Used on breadboard only			

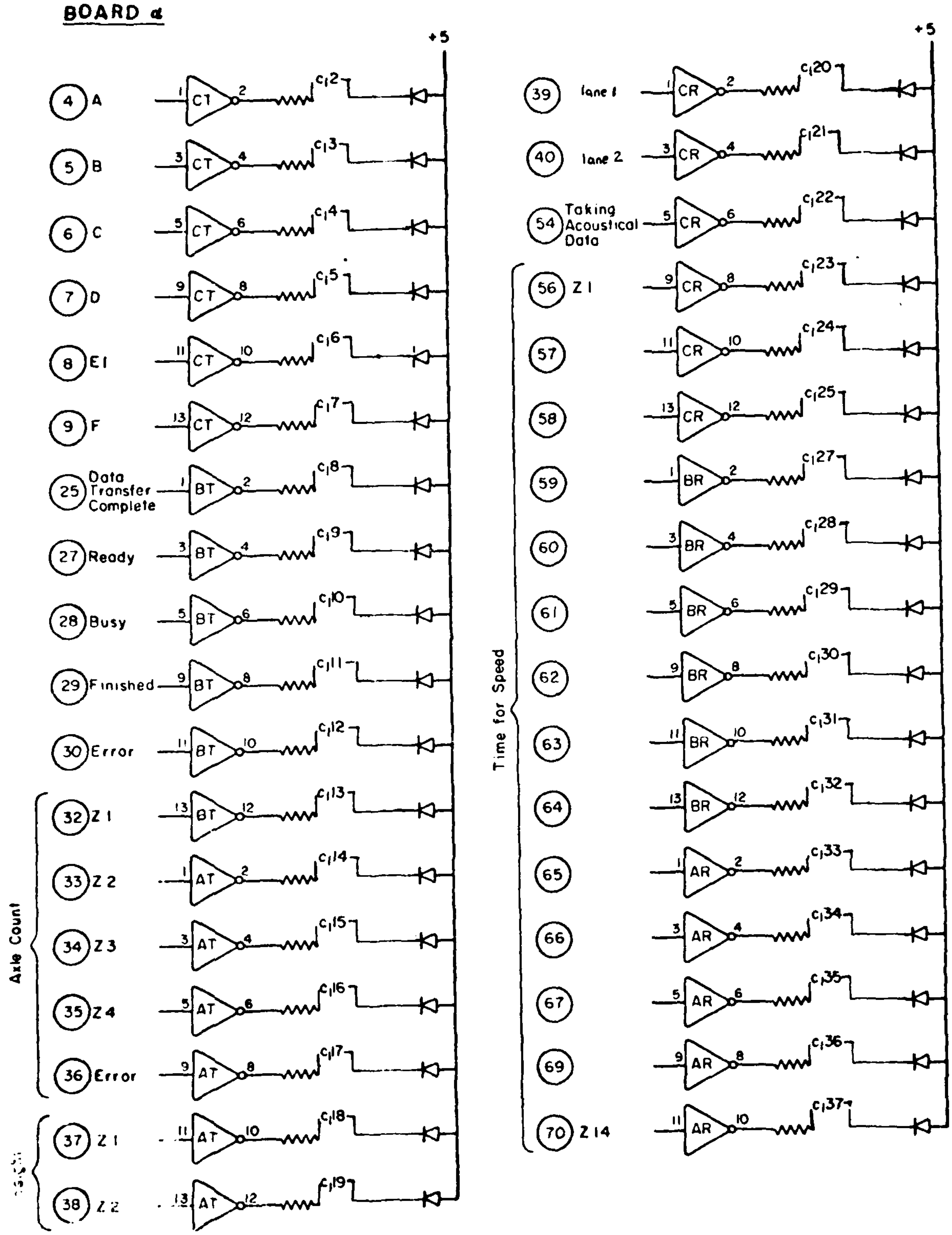
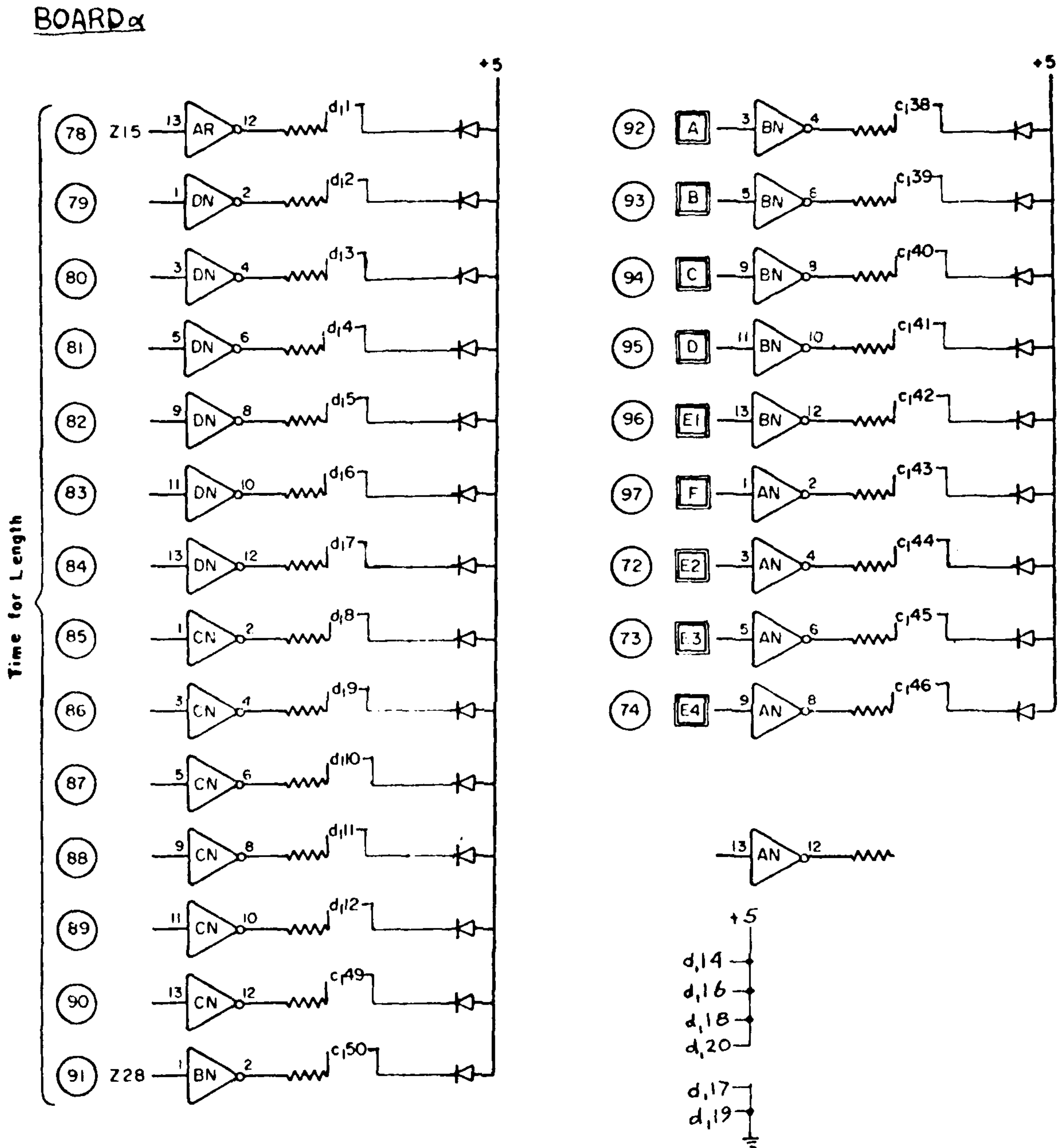


Figure 23a. Schematic of DISPLAY DRIVERS.



Note: All resistors are 220Ω;
All diodes are red LED's located on the front panel.

Figure 23b. Schematic of DISPLAY DRIVERS.

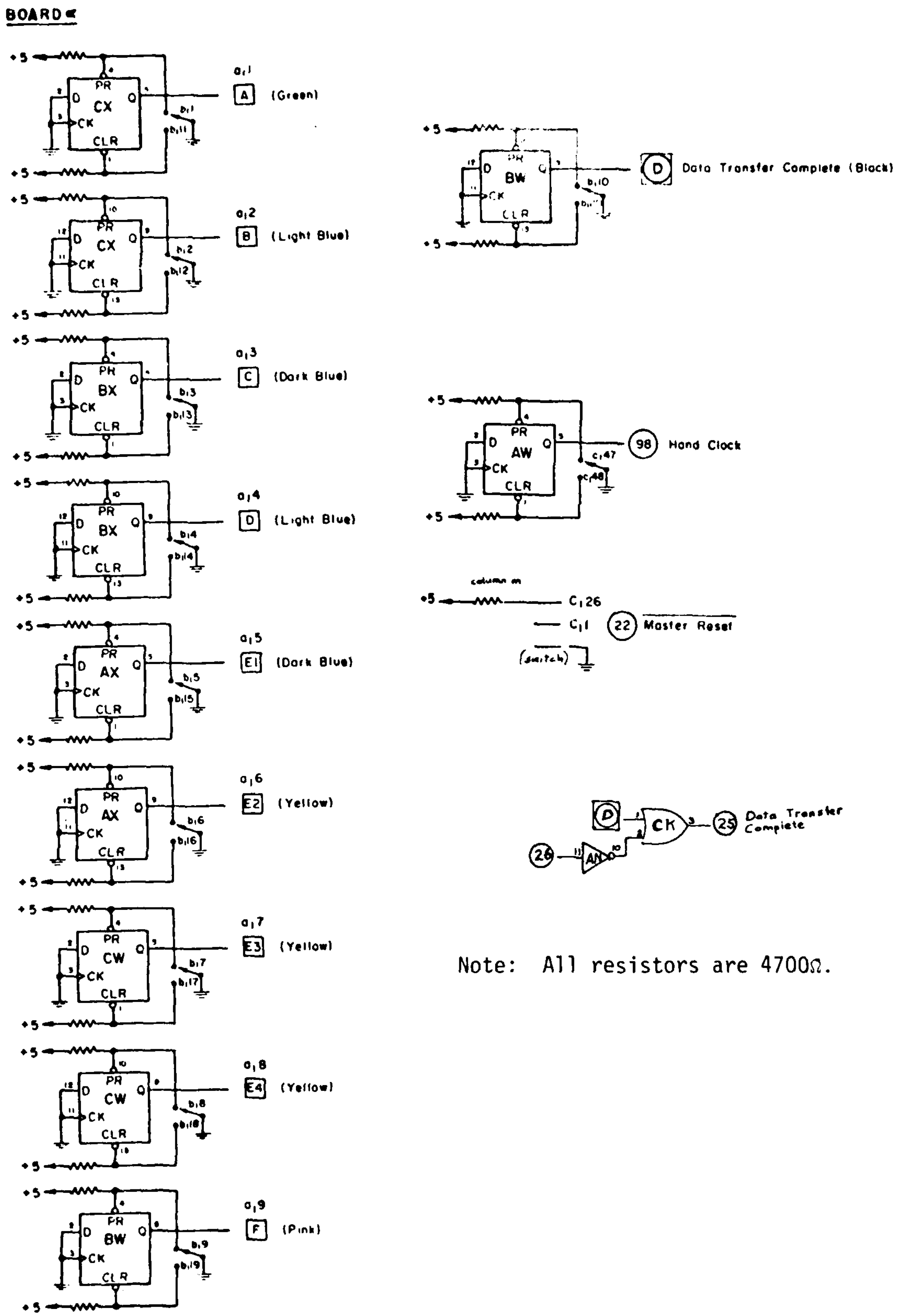


Figure 24. Schematic of Switch debounce.

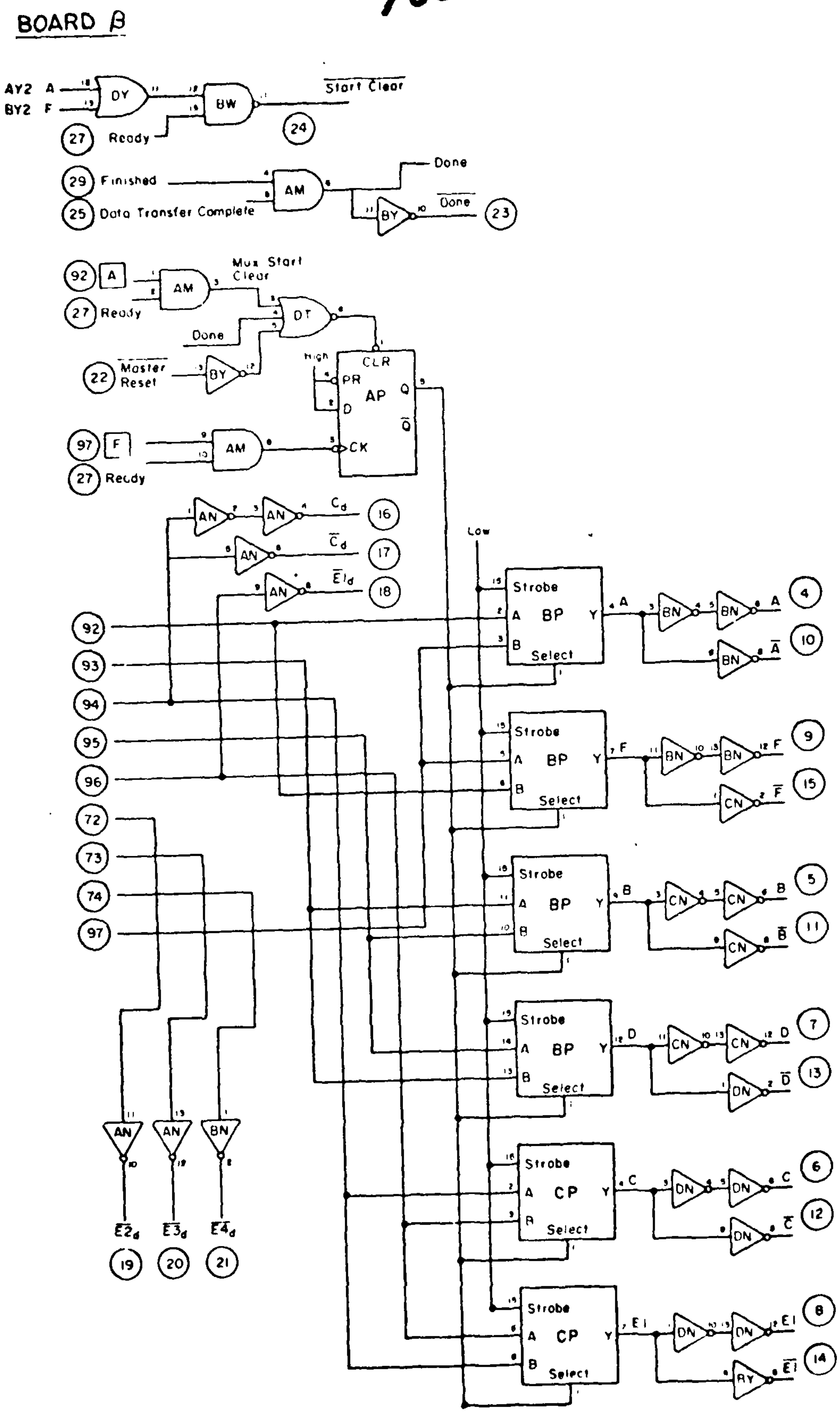


Figure 25. Schematic of Multiplexor.

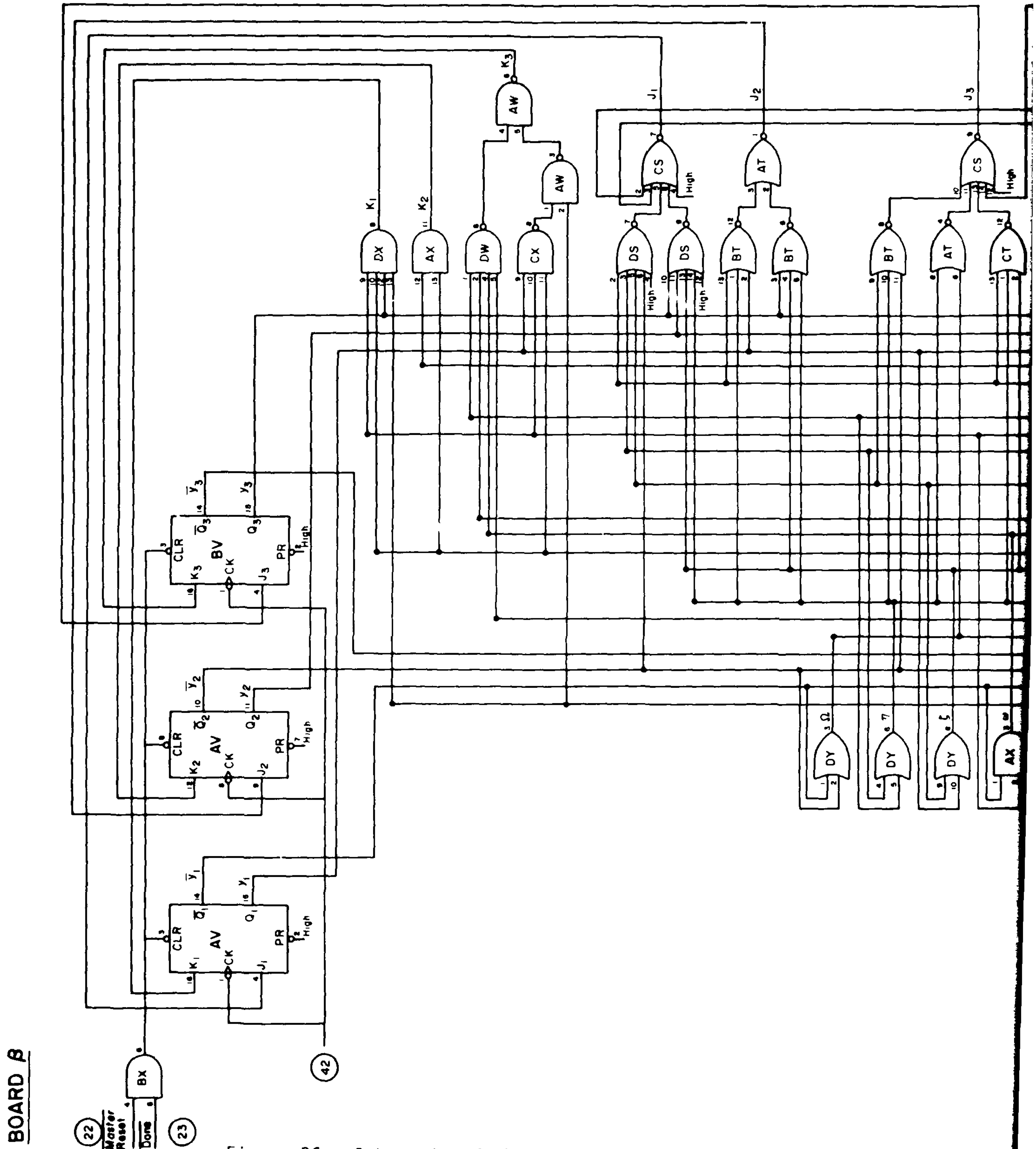
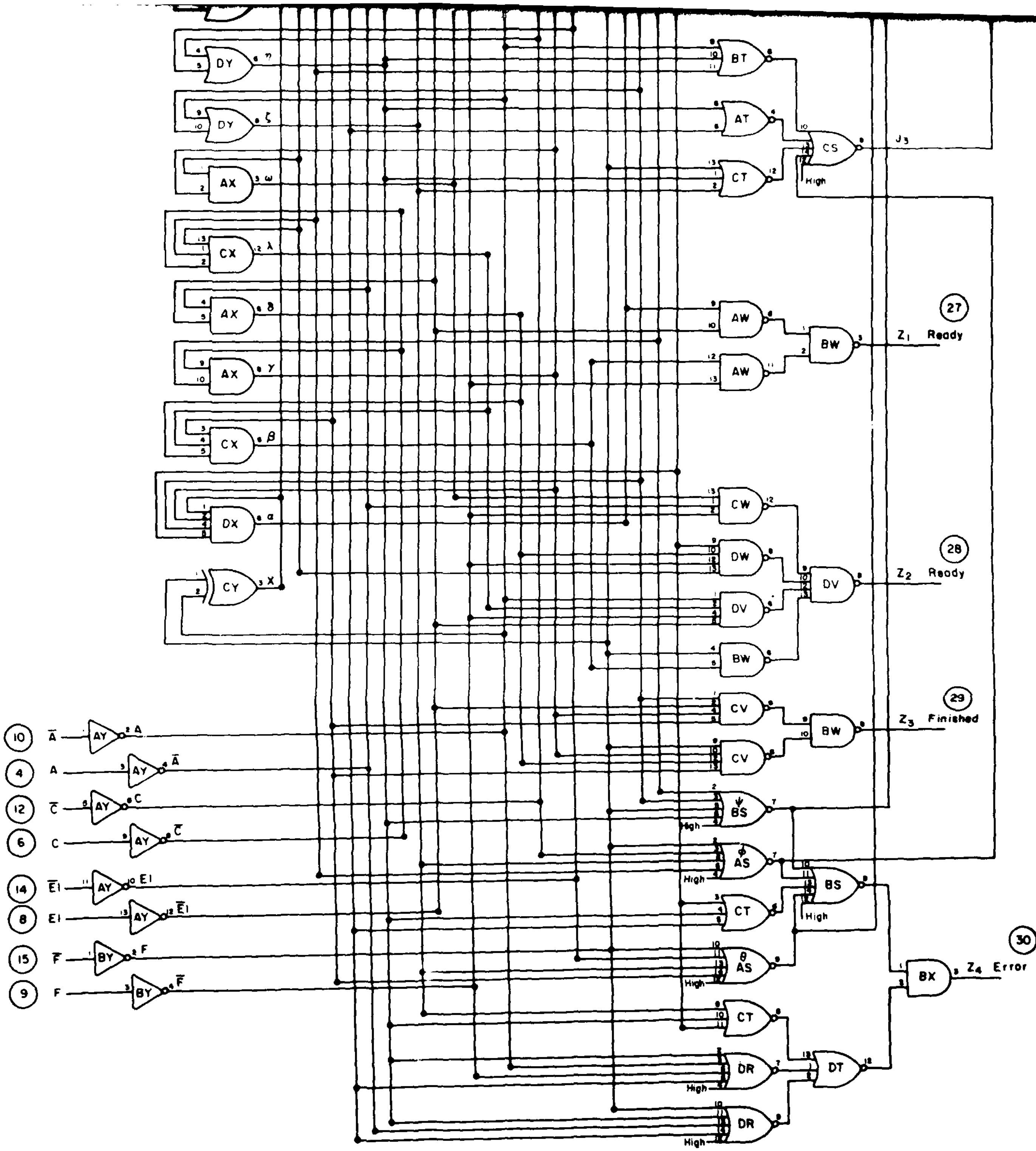


Figure 26. Schematic of SYSTEM CONTROLLER.



J_3
27 Z_1 Ready
28 Z_2 Ready
29 Z_3 Finished
30 Z_4 Error
10 $\bar{A}$
4 A
12 $\bar{C}$
6 C
14 $\overline{E1}$
8 E1
15 $\bar{F}$
9 F

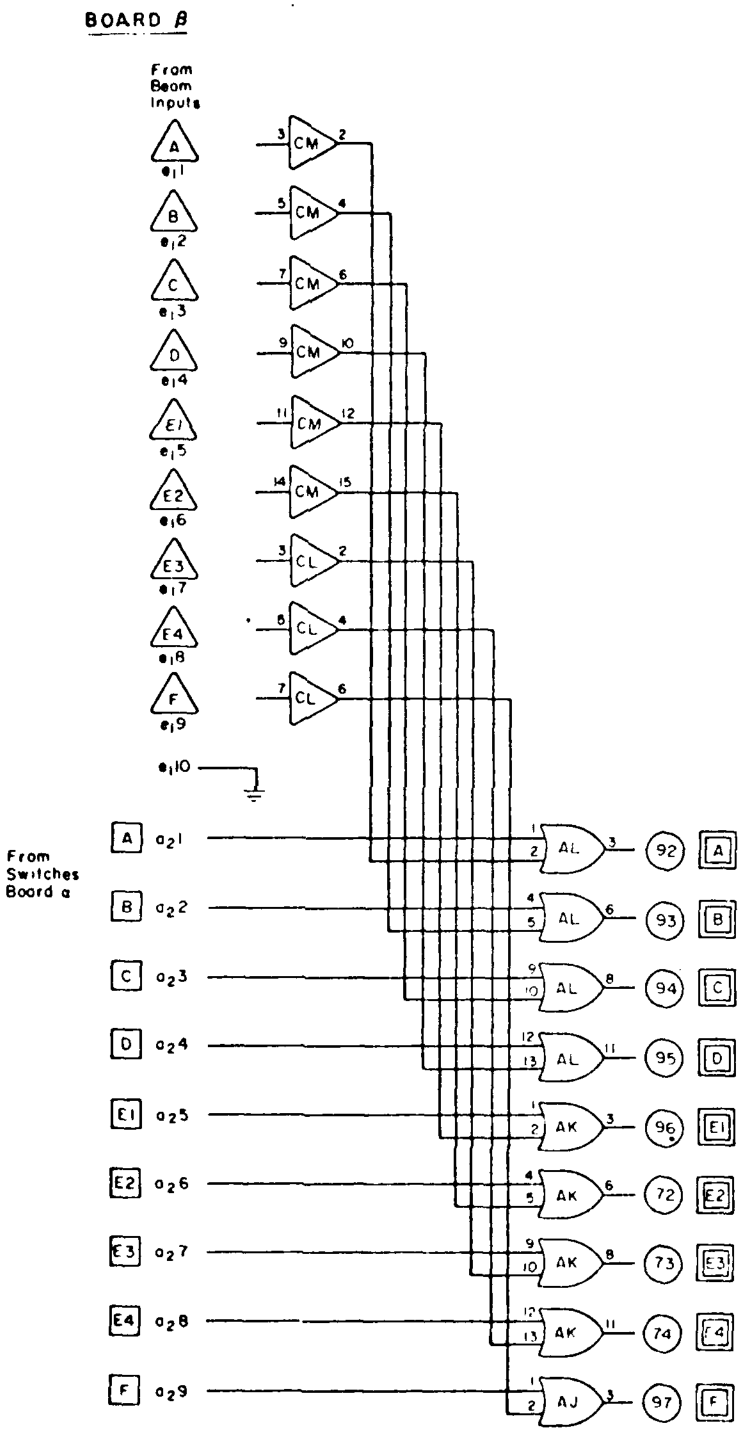


Figure 27. Schematic of Input buffers.

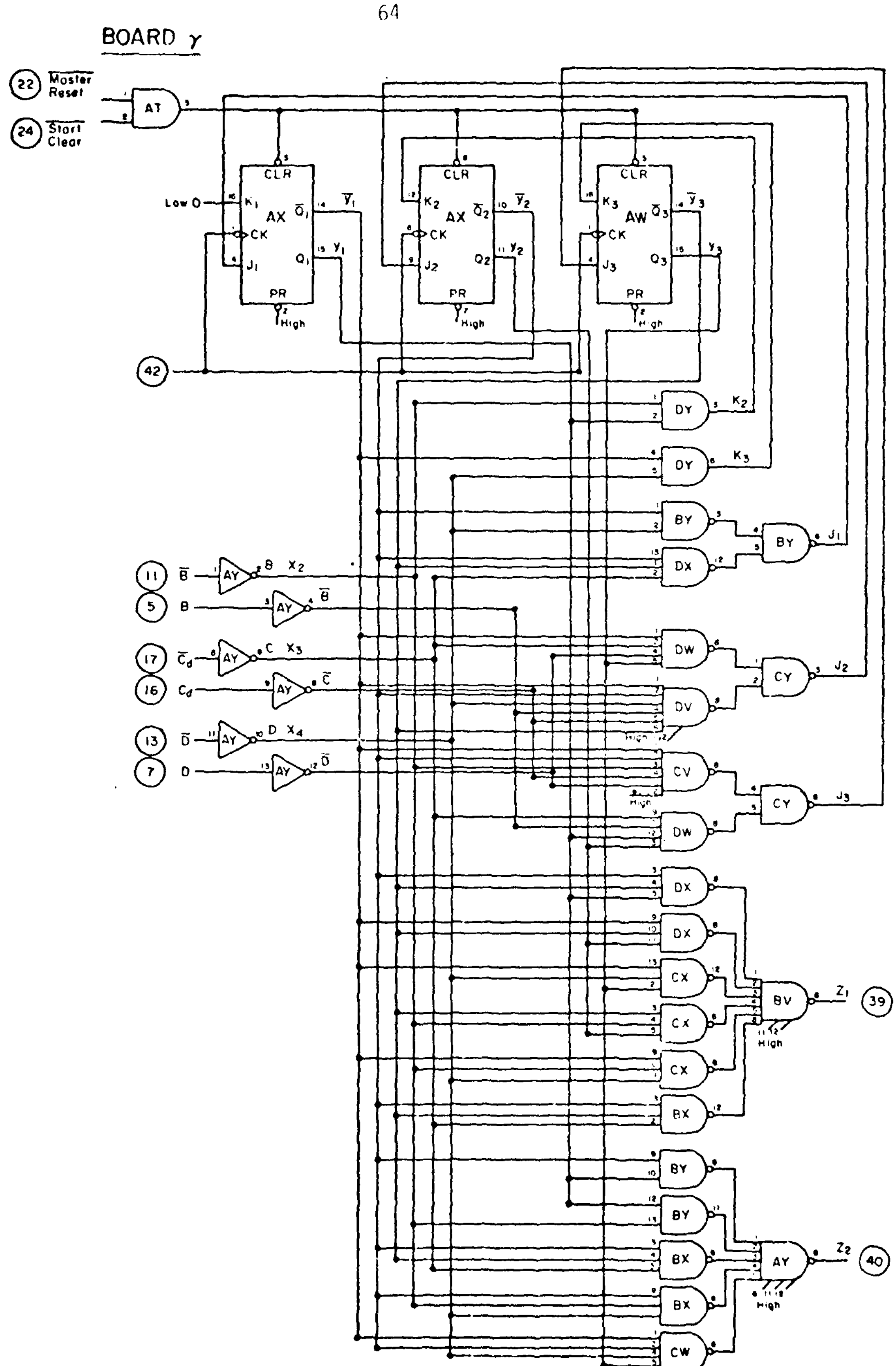


Figure 28. Schematic of LANE POSITION function.

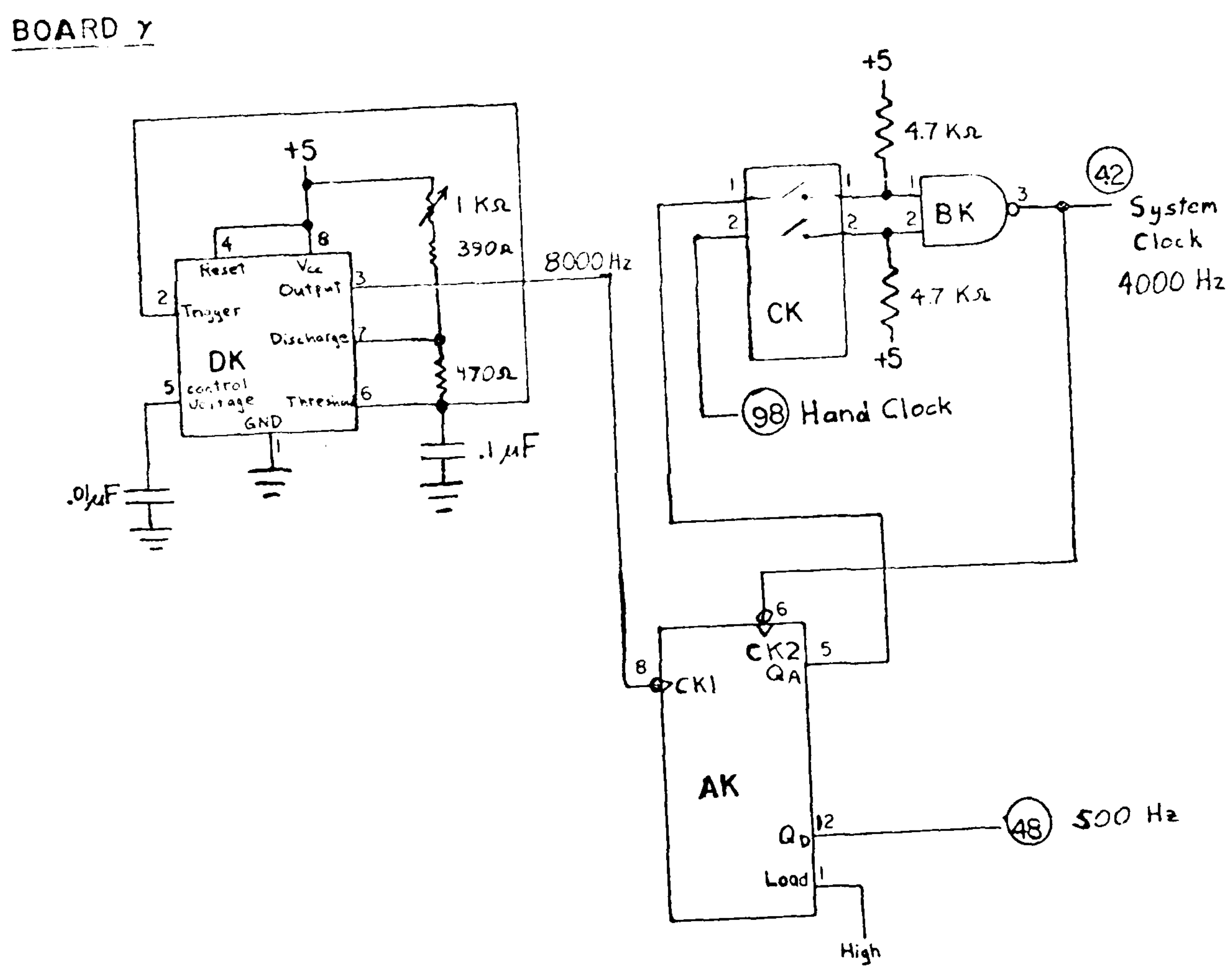


Figure 29. Schematic of CLOCK section.

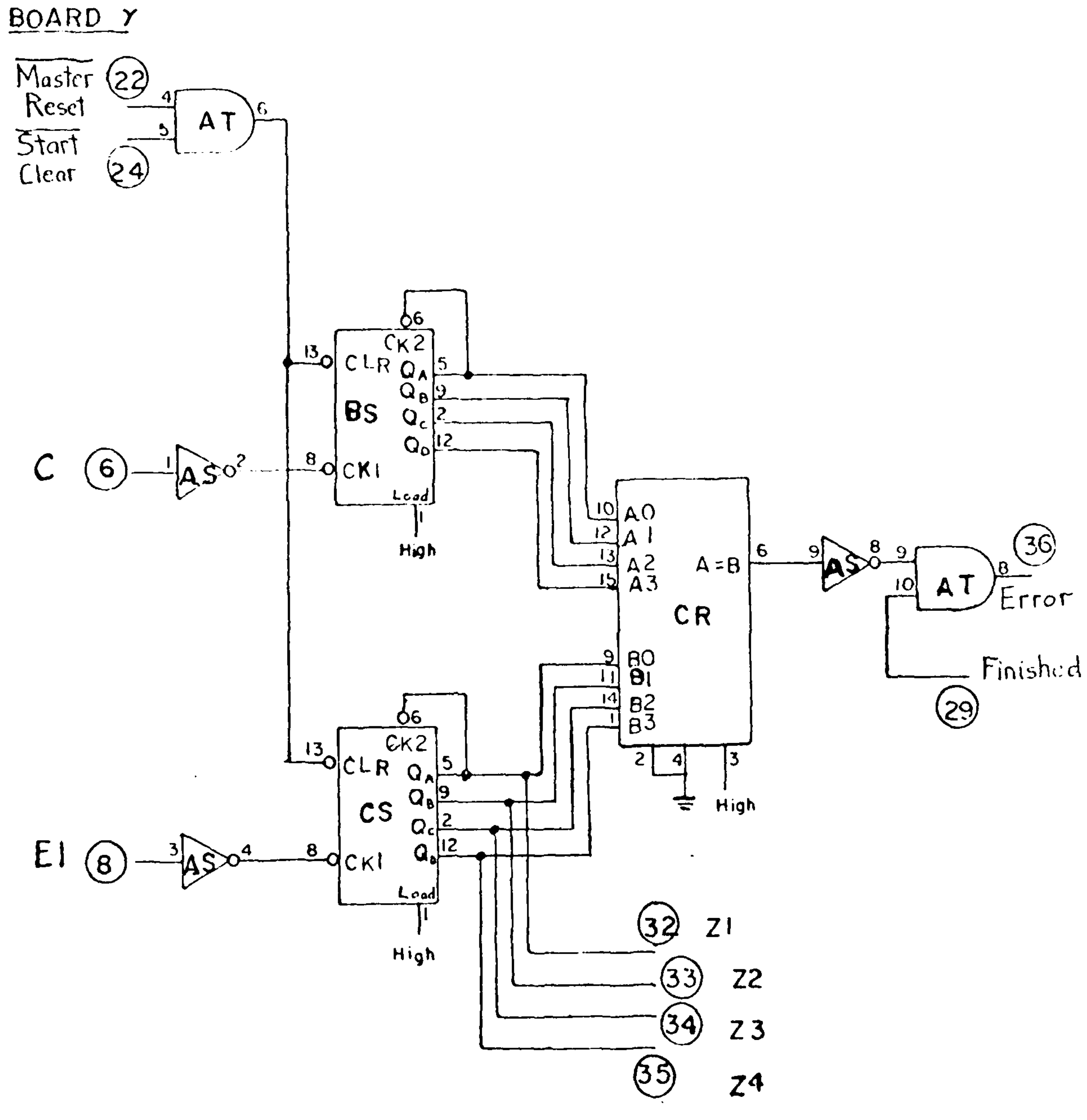


Figure 30. Schematic of AXLE COUNTER function.

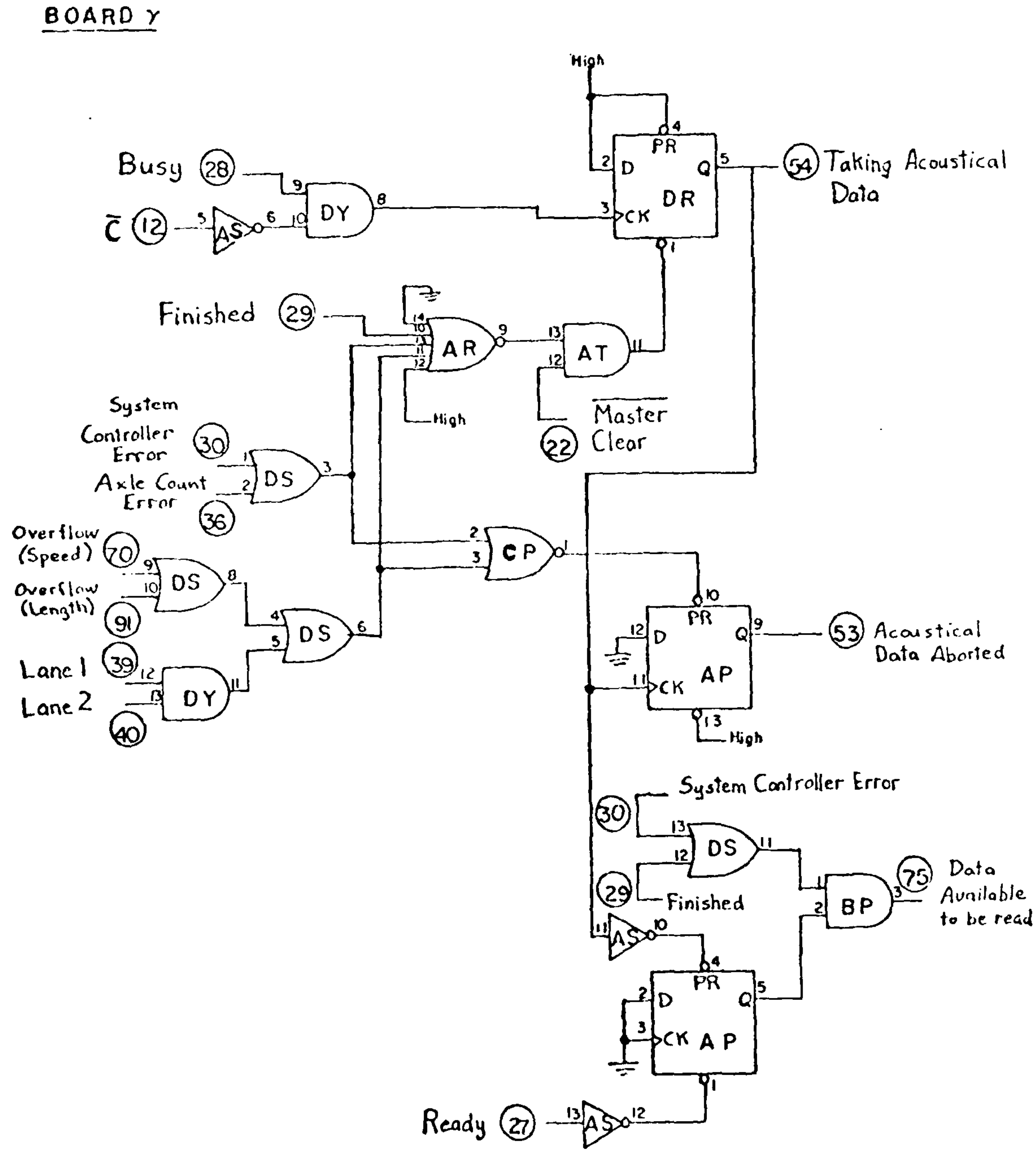


Figure 31. Schematic of section which signals external units.

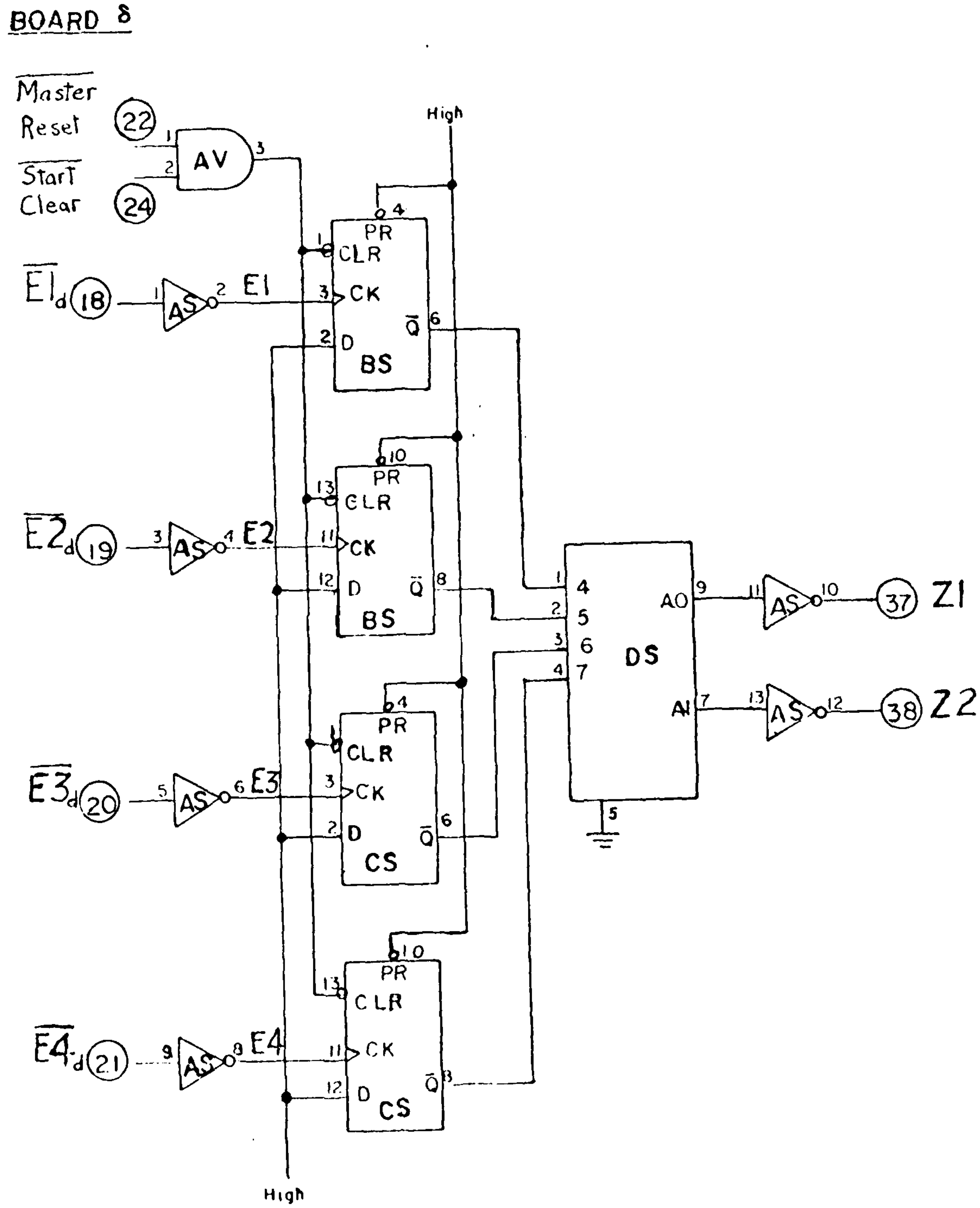


Figure 32. Schematic of HEIGHT function.

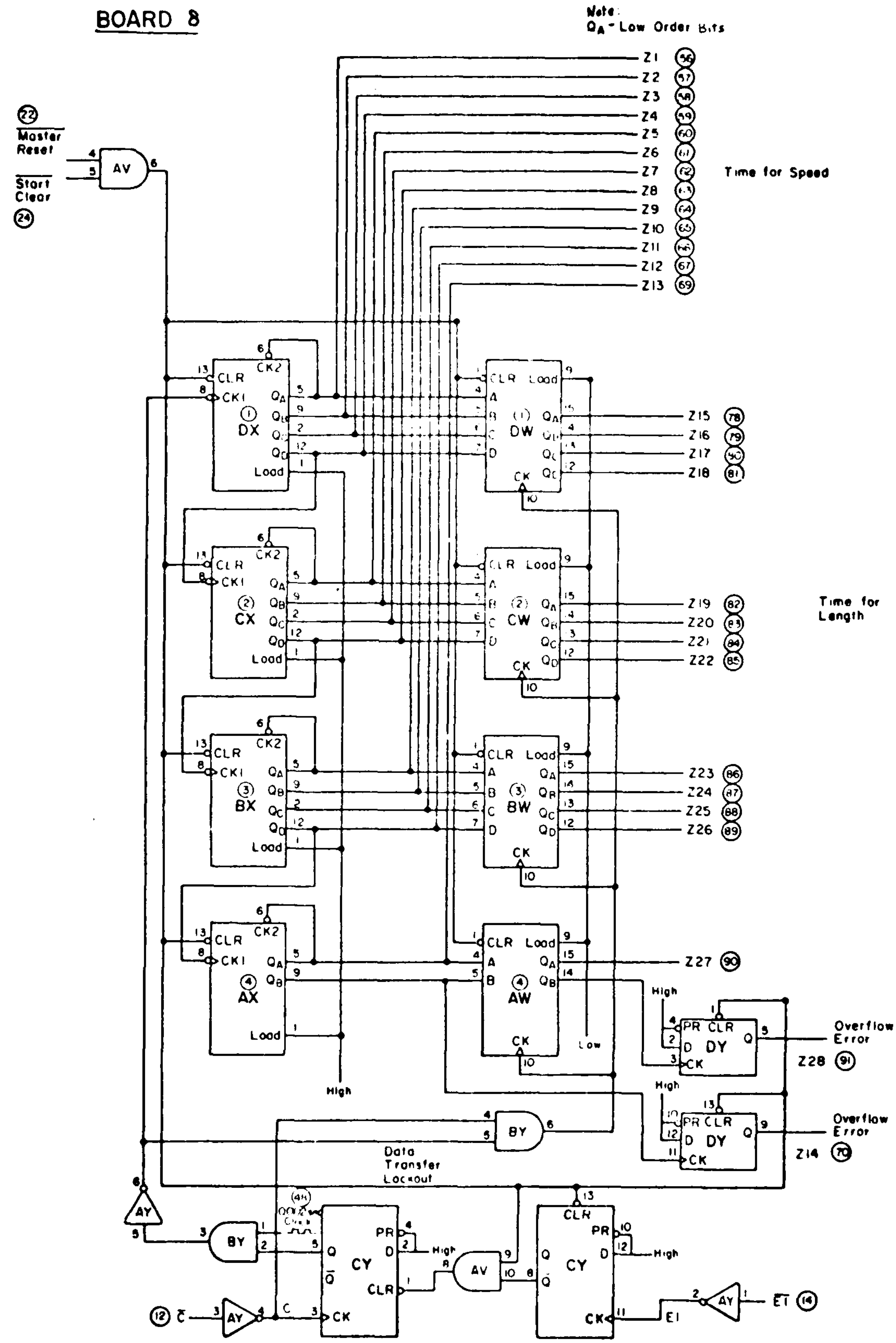


Figure 33. Schematic of SPEED and LENGTH functions.

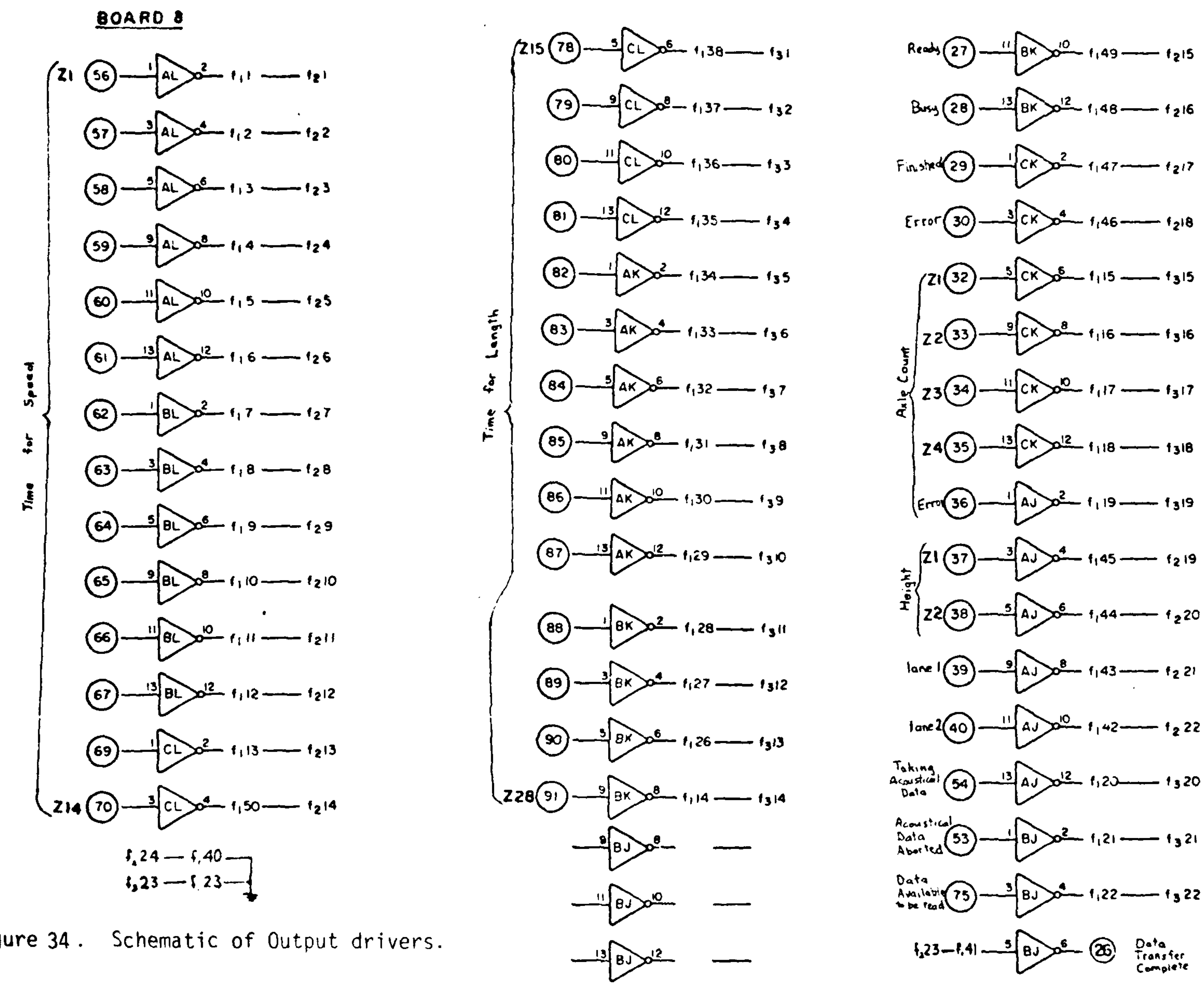
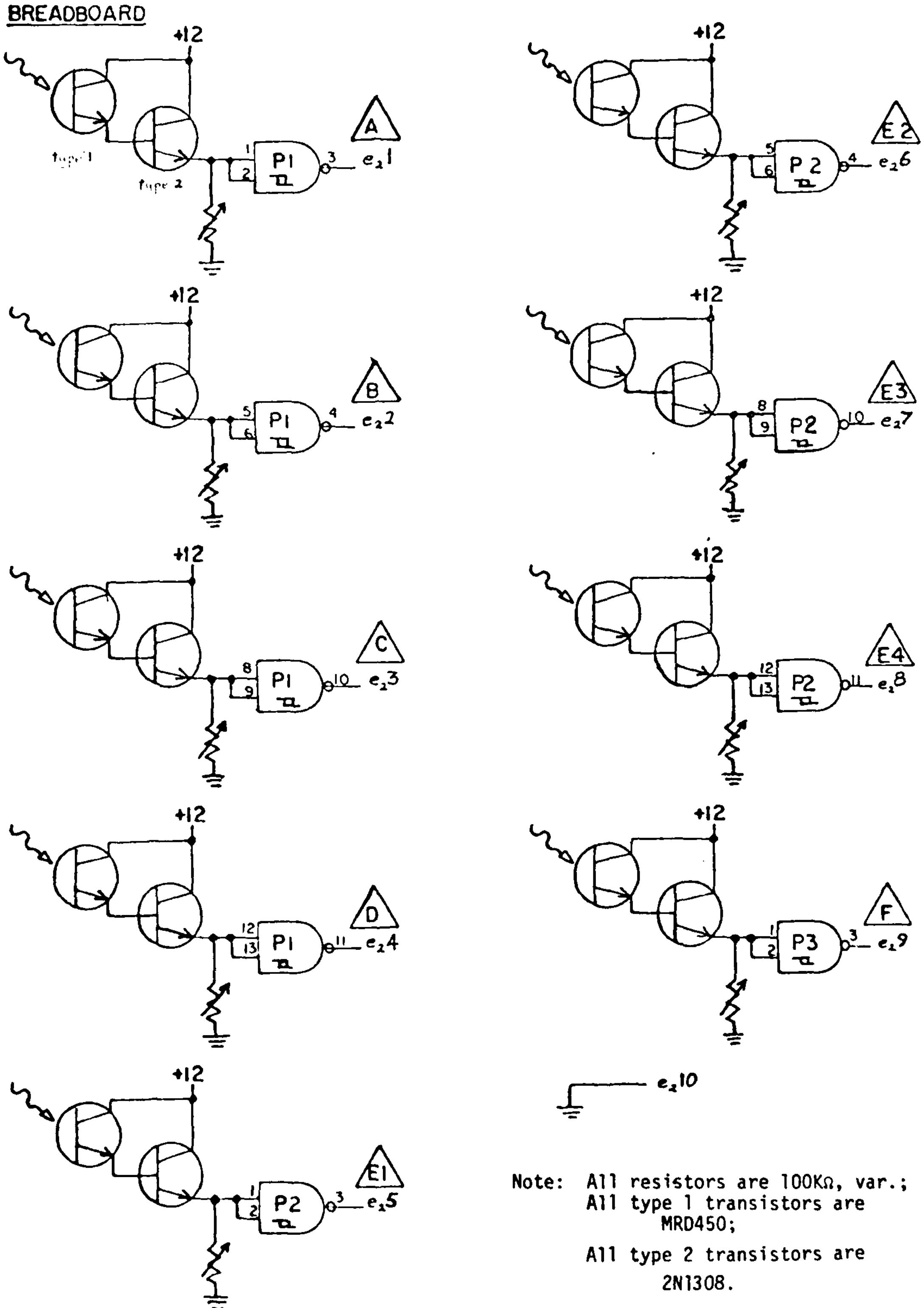


Figure 34. Schematic of Output drivers.



Note: All resistors are 100KΩ, var.;
All type 1 transistors are MRD450;
All type 2 transistors are 2N1308.

Figure 35. Schematic of model receiver units.

APPENDIX C - Model Results

Table 7. Sample test results from system model.

Vehicle		1	2	3	4	5	6	7	8	9	10	11
Length (m)		2.82	3.07	3.40	3.61	3.76	16.41	19.45	4.17	7.21	3.29	1.98
Direction	L to R	*	*	*				*	*	*		
	R to L				*	*	*				*	*
Position	lane 1		*	*		*	*	*	*		*	
	lane 2	*			*					*		*
Height		0	0	0	0	0	3	3	2	2	1	0
Axle Count		2	2	2	2	2	5	5	2	2	2	2
Speed (km/hr)		57.6	105.	103.7	97.7	98.7	110.	53.1	68.1	56.8	65.0	63.2
Length(m)		2.79	3.15	3.40	3.58	3.89	16.5	19.24	4.01	7.14	3.21	2.25
Speed (stopwatch)		61.7	108.	99.	98.2	108.	120.	56.8	67.5	51.4	63.5	61.7

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